BASALTIC STONE - DUST MEDIA FOR WATER FILTRATION

A Thesis Submitted
in Partial Fulfilment of the Requirements
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DOCTOR OF PHILOSOPHY

By

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CERTIFICATE

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NOMENCLATURE OF MATHEMATICAL SYMBOLS

C	rate factor parameter
c	concentration of effluent turbidity
c_o	concentration of influent turbidity
d_m	geometric mean diameter of filter media
d_p	diameter of suspended particle
f_o	porosity of clean filter bed
f_t	porosity of filter bed at time t
g	constant of acceleration due to gravity
h_o	headloss for clean bed
h_t	headloss at time t
K	constant
k	Boltzmann constant
l	distance from inlet face
R	Reynolds number
T	temperature
t	time of filter run
V_o	face velocity of influent water
x, y, z $\alpha, \beta, \gamma, \delta$	constants
η	transport efficiency of individual grains
λ_o	clean bed filter coefficient
λ_t	filter coefficient at time t
μ	absolute viscosity
ν	kinematic viscosity

ϕ	rate factor parameter
ρ_p	density of particle
ρ_w	density of water
σ	specific deposit
σ_u	ultimate specific deposit
ζ_m	zeta potential of media
ζ_p	zeta potential of particle

SYNOPSIS

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The present study aimed at investigating the potential usefulness of a basaltic stone-dust media for water filtration. The present problem stemmed from the situation prevailing in the State of Madhya Pradesh, India where sand of required quality for filter media generally needs to be transported through a long distance. On the other hand, basaltic stone-dust residue is available plentifully near the quarries scattered throughout the State. This departure from the traditional, i.e., substitution of the basaltic stone-dust for sand as a filter media, was substantiated through a systematic laboratory investigation in terms of the physicochemical characteristics of the proposed media in reference to sand and laboratory as well as pilot plant filtration experiments.

The laboratory work consisted of (i) investigation of the potential usefulness of the stone-dust media, in reference to sand, based on its physicochemical characteristics, (ii) assessment of the suitability of the stone-dust media in

reference to sand using the filterability number concept, and (iii) a comparative evaluation of the stone-dust and sand media using parallel laboratory filtration experiments employing 68 cm media depth in 25 mm ID glass filter columns and under identical conditions of media size (d_m 0.46, 0.54, and 0.65 mm), filtration rate (V_o 5, 7.5, and 10 m/h), and influent turbidity level (c_o 10, and 25 NTU). The influent suspension was a coagulated and settled water obtained through batch alum coagulation of a "raw water" prepared in the laboratory using I.I.T. Kanpur tap water and the Lower Ganga Canal sediment.

The physicochemical characterization of the stone-dust indicated its potential suitability as a filter media, inspite of some limitations, e.g., greater susceptibility to attrition/abrasion, higher backwash water rate requirement and lower amount of usable material from the stack. However, the plus points were lower cost, ready availability and lower initial headloss coefficient. Low filterability number values for the stone-dust and comparable to those for sand in terms of the order of magnitude indicated the filtration suitability of the stone-dust media for alum coagulated suspension. The results of the laboratory filtration experiments indicated that, for both the media, effluent turbidity during a filter run improved in the initial stages and deteriorated gradually thereafter but the value at the end of a run was always less than 2 NTU. With the stone-dust media, headloss values were lower at the same time effluent turbidity was comparable to

that obtained in the sand filter. Clean bed filter coefficient values indicated that the stone-dust filter was less sensitive to fluctuations in influent turbidity and filtration rate. Significantly higher ultimate specific deposit values for the stone-dust filter indicated its greater storage capacity for turbidity.

The pilot plant studies, employing the stone-dust as well as traditional sand media, were conducted for a duration of eleven months at the Laxminarayana Giri Water Treatment Plant, Bhopal, Madhya Pradesh to confirm some of the significant observations of the laboratory filtration experiments. Performance data for two filters (e.s. 0.63 mm, and u.c. 1.55; bed depth 45 cm) were collected in parallel under various filtration practices, e.g., constant rate, declining rate and direct filtration. The pilot plant study demonstrated the usefulness of the stone-dust media for traditional constant rate filtration. It produced longer filter runs with effluent quality comparable to that of the sand filter and lower backwash water requirement. In declining rate filtration, the reduction in filtration rate during a filter run was lesser in the stone-dust filter. The stone-dust filter was also found suitable for direct filtration.

1. GENESIS OF THE PROBLEM

1.1 Introduction

The role of adequately treated water in prevention of epidermics of waterborne diseases has been proved beyond doubt. Since independence the Government of India has been trying to improve the status of drinking water supply in the rural as well as in urban areas. A financial outlay of 16,320 million rupees has been made for the water supply and sanitation program in the Sixth Five Year Plan (1980-85). This amount appears inadequate considering that a total outlay of 92,000 million rupees will be required for the 1980-1990 decade program in order to provide safe water supply in terms of the target set by the United Nations Water Conference (Sundaresan, 1979). In a developing country such as India, design of inexpensive and simple, yet efficient water treatment plants to give aesthetically acceptable and safe water supply is the basic need. All possible attempts should be made to build cheaper treatment plants utilizing inexpensive, locally available material and indigenous technology.

1.2 Filtration - a key water treatment process

Among the various treatment processes employed in water treatment, filtration is an important physico-chemical process. This process involves retention of suspended and colloidal particles by the filter media grains

(or previously attached particles) as the water containing these particles is made to pass through the filter. This treatment process has been generally accepted as one of the satisfactory means of controlling the water quality parameters such as turbidity and bacteria, and prepares the water for effective disinfection. Thus, it is expected to overcome all incidental human error in total pretreatment operation. Inspite of improvement in the quality of water by the pre-treatment units, filtration still remains as an indispensable process of water treatment for surface waters.

Agrawal (1966) reported the findings of the East Bay Municipal Utilities, District, California, U.S.A. showing the various alternatives for treated water to be produced at the lowest cost. The study indicated that any combination of granular filter with other treatment methods can be satisfactorily used to give the required quality of water, but the alternative using filtration as a single treatment gives significant savings in capital and operating cost. On the other hand, adequate pretreatment without filtration, but with terminal chlorination is no substitute for filtration (Ghosh, 1961).

1.3 Filter media

Out of the various components of a filtration plant, filter media forms a substantial part of the total cost especially when media of required specification is not

available nearby and has to be brought from a long distance. Sand has been traditionally used as a single filter media. Since last two decades use and suitability of various locally available, cheap material such as anthracite, garnet, alumina, crushed glass, shreded coconut shells, etc. have been demonstrated (Frankel, 1974), but the materials of engineering interest have been limited to anthracite and garnet which have found their application in dual- and multi-media filters.

In India, sand still enjoys the monopoly as a filter media. Anthracite of suitable quality is not available in this country. However, several bituminous coal samples have been recommended as a substitute for anthracite for use in dual-media filtration (Technical Digest, 1971a). Ranade (1976) was perhaps the first to report conversion of a single-media sand filter to a dual-media coal-sand filter at the Kanpur Water Works. He obtained increased yield of the product water from 8 to 30 mld (2.11 to 7.92 mgd) with only an additional expenditure of Rs. 45,000 for conversion. Kardile (1978) tried crushed coconut shell in a number of rural water supply plants in Maharashtra and reported satisfactory performance of the plants. Varghese (1980) carried out laboratory investigation on the potential of crushed coconut shell as a filter media for various conditions of pretreatment. Using the filterability number concept (Ives, 1978), she observed superior performance of this media over the conventional sand media. On a laboratory scale,

Bhole and Nashikar (1974) investigated the use of berry seeds as a filter media. Tiwari (1971) reported the usefulness of cinder as a filter media in combination with sand. However, dual-media filters require adequate pretreatment control of the quality of the influent water and skilled supervision-conditions which are difficult to obtain at most places in India (Technical Digest, 1971b).

1.4 Basaltic stone-dust - the proposed media

In many cases, sand of required quality and size may not be available locally and is required to be transported over a long distance thereby increasing the cost of the filtration plant. In Madhya Pradesh, locally available sand is not suitable as a filter media and is required to be brought from a distance as far as 80 km. The transportation cost has been reported as Rs. 7.5 per km per 100 cum of material (Jagannath Rao, 1979a). Search for an alternative low cost material available nearby is thus desirable. On the other hand, extensive deposits of basalt exist throughout the State. Geological map of Madhya Pradesh indicates that these deposits form about 60 percent of the area of State. This stone is taken out from quarries by blasting and put into crushers to get smaller sized stones. These crushers are located at every important town and district headquarter of the State. From the crusher, various sizes of stones are segregated according to the requirement and stacked separately.

After all the useful sizes are taken out, the residue contains the stone-dust and small sized particles and is stacked separately. This residue is a waste material. Quantity of this material varies from 12 to 14 percent of the initial amount of stone put into the crusher. The present work was aimed at investigating the potential of using this waste material as a filter media. As no crushing for sizing of media is involved, the media of required specification may be prepared after sieving only and will be referred to as 'stone-dust' hereinafter.

Jagannath Rao (1979b) conducted limited experimental work on a pilot plant with the stone-dust media at Bhopal Water Treatment plant. The results of the work indicated the potential suitability of this media for high rate filters. He recommended adequate pretreatment control to limit the turbidity of the filter influent to 20 JTU. However, the study was not conducted in a systematic manner and adequate attention was not paid to the important system parameters. Also, the pilot plant study was not supported by background studies on media evaluation in terms of its physicochemical characteristics in reference to sand and its behaviour as a filter media against sand incorporating the significant filtration parameters. The stone-dust being a crushed material and apparently more angular as compared to sand with consequent high bed porosity presumably had a greater storage capacity for particulate matter removal during

filtration. It was felt appropriate, therefore, to obtain more information through laboratory as well as pilot plant studies with a view to demonstrate applicability of stone-dust media for water filtration.

2. FILTRATION IN WATER TREATMENT

2.1 History and development of water filters

Filtration through a porous media, as a natural process for cleaning water, has been recognized since ages. Nature provides for clean water in the form of hill springs and wells from where man has known its benefits. Need for water filtration was realized as early as 2000 B.C. Slow sand filter, in which natural process of filtration was accelerated, was first installed in the year 1830. Inspite of simplicity of its operation and absence of mechanical equipments for washing, this filter was gradually replaced by rapid sand filters, with chemical pretreatment, which could be operated at much higher rates.

Earlier design and operation of filters involved parameters such as effluent quality, headloss and backwash water requirement. During the last four decades various investigators have made attempts to represent filter performance in terms of mathematical expressions and models. Recent trend in filtration research has been to investigate various modifications of the conventional filter so as to get increased efficiency and better quality of product water. This has led to the adoption of dual- and multi-media filters, use of filter aids and innovation in techniques of backwashing.

2.2 Removal mechanisms

According to O'Melia and Stumm (1967), the mechanisms, for removal of particulate matter in a deep bed filter, consist of two principal steps, viz., transport and attachment. The flow in a filter is of laminar type with low values of Reynolds number. Flow is of Poisseuille type with fluid velocity being maximum at the centre of pore and reducing to zero at the surface of the media grain. Transport mechanisms are required to provide forces so that particles move out of their flow streamlines into the proximity of the filter media grain surface. In attachment mechanisms, the suspended matters which have come closer to the grain surface are attached to it. Mechanisms for attachment are not as well formulated or understood as those for transport. It is understood that attachment is by low energy bonds which are weak in nature.

The third mechanism which is not fully agreed upon by all investigators is detachment where the particles attached to the surface of media are detached and go back to the pores. These may get redeposited on succeeding layer of the media. Detachment is more significant during backwashing operation.

2.3 Transport mechanisms

The various mechanisms which act independently or in combination with one another for transport of particulate matter include mechanical straining, sedimentation, inertia, interception, diffusion, and hydrodynamic forces.

2.3.1 Mechanical straining

This mechanism consists of entrapment of particles at the junction of filter media grains and small pore openings. This phenomena predominates at the liquid interface and at the top of the filter media. For significant removal due to this mechanism, the particle to grain size ratio should be more than 0.05 (Herzig, Leclerc and LeGoff, 1970). Hall (1957) presented rigorous mathematical analysis based on straining action occurring at narrow corners of interstices between the filter grain. According to him the clean bed filter coefficient (a measure of the efficiency of filtration and expressed as the log of ratio of effluent to influent turbidity divided by the depth of filter media), λ_o, is given by

$$\lambda_o = 3.5\, d_p^{1.5}\, d_m^{-2.5} \qquad 2.1$$

where, d_p = size of particle, and

d_m = geometric mean size of media.

Values of λ_o computed using this expression are always on the higher side as compared to the actual observations. This is because bulk of the suspension flows through the central portion of the pore space due to the laminar nature of flow. In deep bed filters straining does not contribute significantly to the total removal efficiency.

2.3.2 Sedimentation

In this mechanism particles in suspension are assumed to be significantly affected by gravity and they come adjacent to the grain surface. According to Ranz and Wong (1952), clean bed filter coefficient, λ_o, can be expressed as

$$\lambda_o = \frac{g}{12} \frac{(1 - f_o)(\rho_p - \rho_w)}{\mu V_o} \frac{d_p^2}{d_m} \qquad 2.2$$

where, g = acceleration constant due to gravity,

f_o = porosity of clean filter bed,

ρ_p = density of particle,

ρ_w = density of water,

μ = absolute viscosity of water, and

V_o = face velocity of influent water.

The above expression is derived for air filters where flow is horizontal and as such its applicability to down flow water filters has been questioned by Agrawal (1966). In normal rapid sand filters (porosity 0.4) water entering the filter has an approach velocity of 2 mm/sec and hence the mean interstitial velocity is 5 mm/sec while Stokes settling velocity for flocs of density 1.2 g/cu cm and 10 μm particle size is 0.0036 mm/sec indicating low gravitational effect. It appears that this mechanism is significant for slow sand filters where approach velocity of water is quite low.

2.3.3 Inertia

Because of inertial effect particle travelling with a certain velocity due to motion of suspension, may tend to travel in straight lines. At the media grain surface the path of the particle from its flow is deviated and it gets removed. Clean bed filter coefficient, λ_o, due to this mechanism can be expressed as

$$\lambda_o = \frac{(1 - f_o)}{12} \frac{\rho_p V_o d_p^2}{\mu d_m^2} \qquad 2.3$$

In air filtration, because of high values of V_o, effect is quite significant while in water filtration the effect has been shown to be negligible (Ison, 1967).

2.3.4 Interception

Interception is the actual physical contact between the suspended particle and the media grain surface and occurs when the particle just touches the surface. Interception effect is independent of the mass or density of the suspended particle but depends on its shape and size. Clean bed filter coefficient, λ_o, is given by (Stein, 1940)

$$\lambda_o = 1.5(1 - f_o) K \frac{d_p^2}{d_m^3} \qquad 2.4$$

where, K = constant.

2.3.5 Diffusion

This is an important transport mechanism for small sized particles less than 1 μm such as bacteria, viruses, etc. Small sized particles have a random movement termed as 'Brownian motion' due to thermal energy of the water molecules. This movement increases with temperature and decreases with increase in size of particle. Due to this movement there is collision between the suspended particle and media grain surface. A concentration gradient is set up and more particles are removed from the bulk fluid. Clean bed filter coefficient, λ_o, is given by (Levich, 1962)

$$\lambda_o = \frac{1.35(1 - f_o)}{d_m} \left[\frac{kT}{d_p d_m V_o}\right]^{2/3} \qquad 2.5$$

where, k = Boltzmann constant, and

T = temperature (degrees, Kelvin).

2.3.6 Hydrodynamic action

A shear field exists in a laminar flow pattern. Due to velocity gradient across the stream lines, a spherical particle rotates and experiences a lateral force. This motion is analogous to the swinging of a spinning cricket ball. The effect is further increased by non uniformity and deformable characteristics of the suspended particle. Using a kaolinite suspension and maintaining the influence of other transport mechanisms constant while varying the Reynolds number, Ison and Ives (1969) explained removal of 10 μm

size particle of 1.005 specific gravity. Efficiency of removal was obtained in the inverse proportion of Reynolds number to the power 2.7.

2.3.7 Combined transport mechanisms

In a real-world system several mechanisms act simultaneously when the influent suspension contains particles of various sizes. In general,diffusion is predominent for submicron particles while sedimentation and interception are more significant for particles of higher density and size greater than 10μm. Ives (1971) proposed a single generalized equation for particle removal due to various mechanisms

$$\lambda_o = \frac{d_p^{\alpha - \beta + 2\gamma}}{\mu^{\beta + \gamma - \delta} \, d_m^{\alpha + \beta + \delta} \, v_o^{\beta + \gamma - \delta}} (kT)^{\beta} \frac{(\rho_s - \rho_w)^{\gamma}}{\rho_w^{\delta}} \qquad 2.6$$

where α, β, γ and δ are constants.

The values of the constants depend upon the nature of suspension, particle size, etc. The above equation indicates a strong influence of particle size and its characteristics, size of media, filtration rate, etc. on removal. Efficiency of removal may be increased by providing gradually finer sized media (as in the case of multi-media filters) or by reversing the direction of flow as in the case of upflow and radial flow filters. In water filtration, minimum efficiency of removal has been reported for 1μm size particles as these are too big to be affected by diffusion and too small to be removed by other mechanisms (Yao, Habibian, and O'Melia, 1971).

2.4 Attachment mechanisms

Once the particle has left its path and come closer to the media grain surface, the next step is its attachment to the surface. This is influenced by surface characteristics of the particles and filter media grains and the distance between the two surfaces. Surface characteristics, in turn, depend on chemistry of the water, e.g., ionic strength and pH. O'Melia and Crapps(1964) reported rapid clogging when zeta potential of the flocs (particles) was changed to positive. Mechanisms for the attachment step include electrical double layer interaction, Van der Waals forces, bridging action due to polymers, and adsorption.

2.4.1 Electrical double layer interaction

Both the media and particulate matter in an aqueous suspension are electrically charged. At their interface potentials arise due to combination of various mechanisms such as unequal dissolution of the constituent ions,ionization of the surface groups, isomorphous substitution, specific adsorption of ions and dipole orientations (Gregory, 1975). As a result of interfacial potential there is distribution of charges between the phases. Since the system is electrically neutral, net charge is zero and this constitutes another layer around the first one, both comprising the electrical double layer. Thickness of this double layer increases with decrease in ionic strength of water. This

indicates greater removal in water having more of total dissolved solids. Electrical double layer is inadequate to explain behaviour in real-world systems as ions in solution are not point charges and the situation is electrokinetic.

2.4.2 Van der Waals forces

With two charged particles of same sign in an aqueous system there exists a combination of force of attraction and repulsion. The magnitude of the attractive force, called the Van der Waals force, varies inversely as the sixth power of the distance while the magnitude of the repulsive force depends on the distance exponentially. The attractive force is operative in a very close range. With increasing distance, the electrostatic repulsive force predominates giving an energy barrier. This barrier is required to be reduced by the addition of destabilizing chemicals causing a reduction in the particle zeta potential.

2.4.3 Bridging action due to polymers

Addition of polyelectrolytes to water enhances attachment by bridging action. Flocs with polyelectrolytes have a greater shear strength (Adin and Rebhun, 1974) and this helps in prevention of turbidity breakthrough. With polyelectrolytes, lower amount of chemical is required and therefore are useful for waters which otherwise would require sweep floc formation in the case of a conventional coagulant like alum.

2.5 Electrokinetic phenomena

According to Agrawal (1966), this phenomena plays a significant role in removal of suspended particles in filtration and constitutes a complete removal mechanism as it takes into account both transport and attachment. Both the particle and media have electrical double layers. Due to the flow of water, double layers surrounding the media grains are continuously sheared off and this sets up a streaming potential which occurs throughout the depth of media. The intensity of this potential in the fluid at a distance of 100μm from the media grain surface is quite significant. The force acting on the particle would be proportional to the product of the field intensity and the charge on the particle. In aqueous system having uniform suspension characteristics, electrokinetic forces would be equal in all directions and the net force would be zero. In a water filter where suspension is not uniform throughout, a concentration gradient is set up from the bulk fluid to the media grain surface. Clean bed filter coefficient, λ_o, due to electrokinetic mechanism is given by (Agrawal, 1966)

$$\lambda_o = \frac{7(1 - f_o)}{d_m} \left[\frac{K_2 z_p^2 N d_m}{\mu V_o} - \frac{K_1 Z_m Z_p d_p}{\mu V_o} \right] \qquad 2.7$$

where, z_p = zeta potential of particle,

z_m = zeta potential of media,

K_1, K_2 = constants, and

N = numerical concentration of particles by volume fraction.

2.6 Detachment mechanism

Detachment of the particle from the surface is primarily due to increased liquid shear stress arising due to increase in interstitial velocity. Detachment occurs when the capacity of the media layer to retain the deposit is exceeded. Behaviour of a detached particle is same as that of any other particle in the suspension and it may be subsequently redeposited in the layer below. Based on adsorption and ion exchange phenomena, Adin, and Rebhun (1977) developed a non-conventional model for predicting concentration of turbidity and headloss in filtration. Detachment was used as one of the parameters and was found to be influenced by the type of suspension and the flow rate. The ultimate detachment occurs when the filter is backwashed.

2.7 Filtration equations

Earlier studies on the filtration was limited to the measurement of headloss, effluent turbidity and backwash water requirement. Since last four decades various investigators have developed mathematical models for effluent turbidity and headloss prediction (Deb, 1969; Ives, 1960; Iwasaki, 1937; Mackrle, Dracka, and Svec, 1965; Maroudas, and Eiskenklam, 1965; Mohanka, 1969; Shaktivadivel, 1966; and Shektman, 1961). Each model was developed for a particular media-suspension system and hence predictions differ widely. All the equations are based on the assumptions of plug flow and negligible dispersion of particulate matter.

2.7.1 Efficiency of filtration

Effluent quality during filtration cycle reflects the efficiency of removal. Iwasaki (1937) was the first to propose a mathematical model for the efficiency of removal of particulate matter. He suggested that change in concentration of suspended solids per unit depth was proportional to the local concentration and expressed it mathematically as

$$-\frac{dc}{dL} = \lambda\ c \qquad 2.8$$

where, c = concentration of the suspended particles at the top of layer dL, and

λ = filter coefficient.

Integration of equation 2.8 gives

$$\frac{c}{c_o} = e^{-\lambda L} \qquad 2.9$$

where, c = effluent quality,

c_o = influent quality, and

L = depth of layer.

During the early stages of filtration, deposits are localized and form domes on the grain surface and this results in increase in the value of the filter coefficient

$$\lambda = \lambda_o + C \sigma \qquad 2.10$$

where, C = rate factor parameter, and

σ = specific deposit (volume of deposit to filter volume).

The period upto which the removal efficiency increases is called the ripening period and is prolonged in case of dilute suspensions. With further accumulation of deposited material, surface area of the media grains is reduced giving increase in interstitial velocity and reduction in the value of the filter coefficient and at one time a non retentive stage is reached. Accordingly Ives (1960) proposed

$$\lambda = \lambda_o + C\sigma - \frac{\phi\sigma^2}{f_o - \sigma} \qquad 2.11$$

where, ϕ = another rate factor parameter.

With sand (density 2.65 g/cu cm and sphericity 0.85) and PVC microsphere (density 1.4 g/cu.cm and 1.3 μ.m) suspension, Ives and Sholji (1965) obtained correlation of λ_o, C and ϕ with filtration rate (V_o), geometric mean size of media (d_m) and absolute viscosity of water (Table 2.1).

Table 2.1 - Effect of variables on λ_o, C and ϕ

Parameter	Equation	Value of constant
λ_o	$\frac{K_1}{V_o\, d_m \mu^2}$	$K_1 = 4 \times 10^{-8}$
C	$\frac{K_2}{V_o\, d_m \mu^{1.2}}$	$K_2 = 0.9 \times 10^{-4}$
ϕ	$\frac{K_3}{V_o\, d_m \mu^2}$	$K_3 = 5.7 \times 10^{-6}$

As the suspended particles are removed from flow, they accumulate in the filter pores. A mass balance of particles in length dL is given by following expression

$$V_o \frac{dc}{dL} + \frac{d\sigma}{dt} = 0 \qquad 2.12$$

Taking into consideration specific surface and interstitial velocity, filter coefficient, λ, at any time t during filtration was correlated with clean bed filter coefficient, λ_o, in a generalised form (Ives, 1971)

$$\frac{\lambda}{\lambda_o} = (1 - \frac{\sigma}{\sigma_u})^x \; (1 + \frac{b\sigma}{f_o})^y \; (1 - \frac{\sigma}{f_o})^z \qquad 2.13$$

where, σ_u = ultimate specific deposit, and

b, x, y, z = constants.

The models of various investigators can be expressed in terms of this general equation by assigning specific values to the constants x, y and z (Table 2.2).

Adin and Rebhun (1977) differentiated practical and theoretical capacity of the filter in terms of storage of deposits within the filter bed. They used the term "capacity ratio" expressed as a ratio of the above capacities. With application of polymer, in place of alum, higher value of capacity ratio was obtained.

Table 2.2 - Mathematical models for filter coefficient

Investigator (1)	Equation (2)	Values of constant (3)
Ives (1960)	$\lambda = \lambda_o + c\sigma - \frac{\phi\sigma^2}{f_o - \sigma}$	$x = y = z = 1$
Shektman (1961)	$\lambda = \lambda_o(1 - \frac{\sigma}{f_o})$	$x = y = 0,\ z = 1$
Maroudas and Eiskenklam (1965)	$\lambda = \lambda_o(1 - \frac{\sigma}{\sigma_u})$	$x = 1,\ y = z = 0$
Mackrle, Dracka and Svec (1965)	$\lambda = \lambda_o(1 + \frac{b}{f_o})^y (1 - \frac{\sigma}{f_o})^z$	$x = 0$

2.7.2 Headloss development

With the passage of the suspension through the porous media deposit accumulation in voids cause reduction in permeability resulting in increased resistance to flow or headloss Even for a clean filter bed there is some resistance to flow and value of headloss for clean bed conditions are given by the Carmon-Kozeny equation

$$h_o = K_o \left(\frac{L_e}{L}\right)^2 \frac{\nu}{g} \frac{(1 - f_o)^2}{f_o^3} V_o S_o^2 \qquad 2.14$$

where, K_o = constant,

L_e/L = tortousity factor,

ν = kinematic viscosity, and

S_o = specific surface.

By substituting K for $K_o(\frac{L_e}{L})^2$ and $\frac{A}{V}$ for S_o, equation 2.14 reduces to the commonly used form

$$h_o = K \frac{\nu}{g} \frac{V_o(1 - f_o)^2}{f_o^3} (\frac{A}{V})^2 \qquad 2.15$$

With progress of filtration, the parameters **which are affected** are, the porosity of filter (f_o) specific surface (S_o), tortousity factor ($\frac{L_e}{L}$), and K_o. Headloss, h, at any time in a filter containing specific deposit, σ , can be expressed in a generalised form (Shaktivadivel, 1966)

$$\frac{h}{h_o} = (1 + \frac{b}{f_o})^{2x} (1 - \frac{\sigma}{f_o})^{2y-3} \qquad 2.16$$

where, b, x, y = constants.

Mathematical models for headloss equation by various investigators are summarized in Table 2.3 showing the specific value of the constants. Comparison of the various equations reveals that for initial flow condition headloss values for various models are similar for a given specific deposit but differ widely during the later stages of filter run. The equations by Deb and Mohanka give lower value of specific deposit for same headloss value.

Table 2.3 - Mathematical models for headloss (Shaktivadivel, Thanikachalam and Seetharaman, 1972).

Investigator (1)	Equation (2)	Remark (3)
Mohanka (1969)	$\frac{h}{h_o} = (1 + \frac{b\sigma}{f_o})^2 (1 - \frac{\sigma}{f_o})^{-1}$	$x = y = 1$
Mackrle, Dracka and Svec (1965)	$\frac{h}{h_o} = (1 + b\frac{\sigma}{f_o})^3 \times (1 - \frac{\sigma}{f_o})^{-1.5}$	$x = 1.5,\ y = 0.75$
Shektman (1961)	$\frac{h}{h_o} = \left[1 - \sqrt{1 - \frac{(f_o - \sigma)}{f_o}}\right]^{-3}$	only f_o term taken into account
Ives (1960)	$h = h_o + K\sigma$	terms of higher order containing σ neglected
Deb (1969)	$\frac{h}{h_o} = (1+G(1-10)^{-K}) \times \frac{f_o}{(f_o - \sigma)}^3$	$G = 3.2,\ K = 13.3$
Shaktivadivel (1966)	$\frac{h}{h_o} = \frac{(1-f_o+\sigma)^2}{(f_o-\sigma)^2} \times \frac{f_o^3}{(1-f_o)^2} \cdot \frac{1}{\xi^2}$	only porosity considered and variables combined as $\xi^2 = (\frac{K_o^*}{K_o})(\frac{L_e^*}{L})^2 (\frac{L}{L_e})^2 \times (\frac{S_o^*}{S_o})^2$

* Values at time t during filtration.

2.8 Operational optimization of filter

For a given size of filter media, influent turbidity and filtration rate, parameters governing operation of the filter cycle are the headloss and effluent turbidity. Filter run is terminated when the effluent turbidity exceeds the acceptable limit or a predetermined headloss is reached. Allowable terminal headloss is predetermined on the basis of depth of water level above the filter bed. In normal operation of filter, headloss consideration governs the filter cycle. Optimum condition is reached when both headloss and effluent turbidity criteria limit the run at the same time (Mintz, 1966). This can be achieved by selecting proper depth and size of media. A graphical method of optimization, using the concept outlined by Mintz (1966), will be covered in details in Chapter 5. With change in filtration rate or media size, another optimum depth is obtained. There exists one media size, depth and filtration rate for which the most optimum condition is reached.

2.9 Models for particle deposition in deep bed filters

A filter bed is considered to be consisting of a series of unit bed elements, each unit consisting of an assembly of particle collectors (Payatakes, Tien and Turian, 1973). In this element the filter coefficient is assumed to be constant. Retention of particulate matter within a filter media can be considered in terms of deposition of particles

from the suspension following collectors of specified geometry. Each model is based on a particular shape and models to represent deposit morphology are capillaric model (Payatakes, Rajagopalan and Tien, 1974), spherical-in-cell model (Yao, Habibian and O'melia, 1971; Payatakes, Rajagopalan and Tien, 1974), and constricted tube model (Payatakes, Tien and Turian, 1974).

In capillaric model, length of capillaries is assumed to be equal to average grain diameter. Capillaric model analysis is simpler as flow is assumed to be one dimensional indicating low effect of radial velocity and giving lower values of clean bed filter coefficient. Spherical-in-cell model as applied by Brinkman (1949) takes into consideration the effect of neighbouring grains. Flow is two dimensional and is described by a combination of the "Navier-Stokes" law (excluding inertial terms) and Darcy equation. Happel (1958) proposed modified spherical-in-cell model containing an outer cell of liquid envelope the diameter of which is expressed in terms of porosity. Happel's model is applicable for particle size greater than 0.09 times grain diameter. Constricted tube model takes into consideration the statistical distribution of pore size and converging and diverging nature of flow.

None of these models are exactly applicable to represent different stages of filtration, viz., ripening followed by gradual deterioration. A comprehensive model

should take into consideration every aspect of deposition process and randomness of grains and pores. A combination of spherical in cell and constricted tube model is presently used to represent the working of filter cycle (Tien, Turian, and Pendse, 1979).

2.10 Indices for filter performance

Inspite of an understanding of the physicochemical properties of the filter media and the suspension, and behaviour of flow through granular filters, it is not possible to predict performance of a specific media-suspension system without elaborate experiments. Several empirical approaches have been proposed to predict filter performance. Gamet and Rademachar (1959) proposed a filter performance index as total gallons of water filtered per foot headloss per square foot of filter media. This index does not take the effluent quality into consideration.

Using sand, Cleasby (1969) expressed filterability by a term filterability index given by

$$F = \frac{\lambda \sigma}{h_f} \qquad 2.17$$

where, λ = filter coefficient,

σ = specific deposit, and

h_f = headloss difference.

To determine this index, values of filter coefficient, specific deposit and headloss parameters are required to be

evaluated by rigorous experimental work. This index gives very high results with uncoagulated clays.

Ives (1978) proposed a simpler dimensionless filterability number which takes into account effluent and influent quality, clogging and flow. Filterability number is expressed as

$$F = h \times \frac{c}{c_o} \times \frac{1}{V_o t} \qquad 2.18$$

where, h = headloss,

c_o = average influent quality (inlet suspension turbidity),

c = average effluent quality (filtrate turbidity),

V_o = approach velocity (filtration rate), and

t = time of filter run.

To determine this number, Ives has suggested filtration of a particular volume of suspension (about 1 l) through a shallow depth of media (40 mm). For interpretation of results, large number of observations are needed. With this tool it is possible to assess the suitability of media-suspension systems. With filterability number values for different depths, it may be possible to screen out some of the variables for subsequent filtration experiments.

2.11 Operational practices

It was customary in the past to operate filters with coagulated and settled water on a constant rate basis which resulted in deterioration of effluent quality with

increase in headloss (Hudson, 1959). Advancement of technology and better understanding of the filtration process has made possible various filtration practices such as constant rate, declining rate and direct filtration.

Constant rate filters are provided with rate-of-flow controllers and they deliver a constant throughput of the filtered water. These type of filters give poor effluent quality particularly with combination of coarser media and higher filtration rate.

In declining rate filters, rate of flow controllers are not provided and the filter influent enters below the low water level. Larger size of influent header minimizes the headloss. Multiple units are required in order to have a constant throughput of filtered water. These filters give better quality of effluent along with greater amount of product water. Advantages of declining rate filters include minimum mechanization, slow starting backwash, elimination of air binding and accessibility of underdrains.

In direct filtration, raw water is mixed with the coagulant and flocculated intensively for a short period and fed directly to the filters. Microflocs are formed and they are removed in the body of the filter media. In this system, both the solids (naturally occurring and added or produced) are stored in the filter. Culp (1977) has indicated the feasibility of this type of filters for raw waters low in turbidity and free from color. Factors governing the

suitability of the process include quantity of product water, quality of filtered water, reduction in the chemical dose and requirement of backwash water (as a percent of output of filtered water).

2.12 Backwashing of filter

Rapid sand filters are cleaned so as to restore their capacity when effluent quality deteriorates beyond an acceptable limit or headloss through filter bed and underdrainage system reaches the predetermined value. Cleaning is done by a combination of flow of water and air or only with water. The attached solids must be released from the filter media and should be removed from the filter. Normal practice is to fluidize the bed by reversing the direction of flow and backwash the filters with 30 to 35 percent bed expansion. Expansion of the bed produced by upflow velocity is a function of the initial porosity.

Hydrodynamic shear is considered to be the chief mode of cleaning (Camp, Graber and Conklin, 1971). Amritharajah (1971) obtained optimum backwashing with porosity of the fluidized bed in the range 0.684-0.756, higher values being required for finer grains. Valencia and Cleasby (1979) applied velocity gradient concept to granular filter backwashing and obtained optimum velocity gradient values for sand and anthracite. Thackwell (1979) gave expression for degree of cleanliness based on percent of unused filter bed,

percent turbidity removal, percent of coliform removal and percent of bacterial removal. With use of alum or ferric coagulant, fluidization backwash may be adequate, as the captured solids have weak adhesive forces (Amirtharajah, 1980).

Various filter backwashing methods include high wash velocity using only water, intermediate washing with use of auxiliary air scour and low wash velocity (subfluidization) with simultaneous application of air and water. High wash velocity needs greater amount of backwash water and hence in tropical countries where temperature is high, combination of air scour and water is used.

3. SCOPE OF THE PRESENT STUDY

The present state of knowledge related to an understanding of the mechanistic and operational aspects of water filtration has evolved through laboratory studies and plant operation employing sand as the traditional filter media. The basic objective of the present study was to investigate the potential usefulness of a locally available, cheap material, i.e., the stone-dust as a filter media. Logically, this departure from the traditional sand was needed to be substantiated through systematic laboratory investigation in terms of the physicochemical characteristics of the proposed media in reference to sand and laboratory as well as pilot plant filtration experiments employing the stone-dust and sand and incorporating the various engineering parameters related to water filtration. The study was undertaken on the following lines:

(1) Investigation of the potential usefulness of the stone-dust media, in reference to sand, based on its physicochemical characteristics.

(2) Assessment of the suitability of the stone-dust media by reference to sand using the filterability number concept (Ives, 1978).

(3) Comparative evaluation of the stone-dust and sand media using parallel laboratory filtration experiments under identical conditions of media size, filtration rate and

influent turbidity. Addition of objectives were to obtain information on operational optima in terms of depth of filter media and length of filter run for a predetermined headloss limit and the influent-effluent turbidity ratio limit and comparative filtration behaviour of the two media in terms of filter coefficient and ultimate specific deposit, and

(4) Confirmation of the significant observations of laboratory filtration experiments through a pilot plant study using the stone-dust and sand media at the Laxminarayana Giri Water Treatment Plant, Bhopal, with an additional objective to demonstrate the applicability of the stone-dust media under various filtration practices (constant rate, declining rate, and direct filtration) and seasonal variation in the raw water quality.

4. CHARACTERIZATION OF THE STONE-DUST AS A FILTER MEDIA

4.1 Criteria for a filter media

A suitable filter media is an essential prerequisite for any filter and a thorough consideration should be given to the selection of the filter media. The traditionally employed sand media is usually characterized in terms of effective size (e.s.) and uniformity coefficient (u.c.), i.e., 10-percentile and ratio of the 60-percentile to the 10-percentile, respectively, and solubility in hydrochloric acid (Cox, 1964). When several potentially useful filter media are available, it becomes necessary to examine their physicochemical characteristics for the conditions to which they are to be exposed and would have a bearing on media performance. The generally accepted criteria for an ideal filter media are (Weber, 1972)

(1) It should be inert, hard and durable,

(2) It should store large quantity of particulate matter with low headloss,

(3) It should be easily cleaned by backwashing,

(4) It should give an effluent of acceptable quality,

(5) It should not leach any undesirable substances which may impair the quality of the filtered water, and

(6) It should be available at a cheap rate.

All these conditions are difficult to satisfy and hence a compromise is necessary particularly when a locally

available material has to be made use of. For characterization of the stone-dust in terms of its use as a filter media with reference to traditional filter sand, tests and procedures suggested by Ives (1969) and Paramasivam and others (1973) were employed. Brief test procedures along with the results obtained and their significance in the filtration process are given below.

4.2 Mechanical analysis

This test gives the percent output of usable material from a stack. A sample of the stone-dust was collected from a crusher located near Panchsheel Nagar, Bhopal while Narmada sand from Hosangabad, Madhya Pradesh was used. This sand is used as a filter media in water treatment plants in Madhya Pradesh. Both the media were sieved through IS sieves and the percent of material passing through each sieve was determined. Because of greater angularity of the stone-dust as compared to sand, a greater time of sieving (8 min) was used as compared to 5 min for sand (O'Connor, 1975). The results of analysis (average of 2 samples) are shown in Fig. 4.1. Percent of usable material for various sizes expressed in terms of effective size (e.s.), uniformity coefficient (u.c.), and geometric mean size (d_m) are shown in Table 4.1.

It is apparent that the effective output for any size is less in the case of the stone-dust as compared to sand. However, ready availability and low transportation cost might

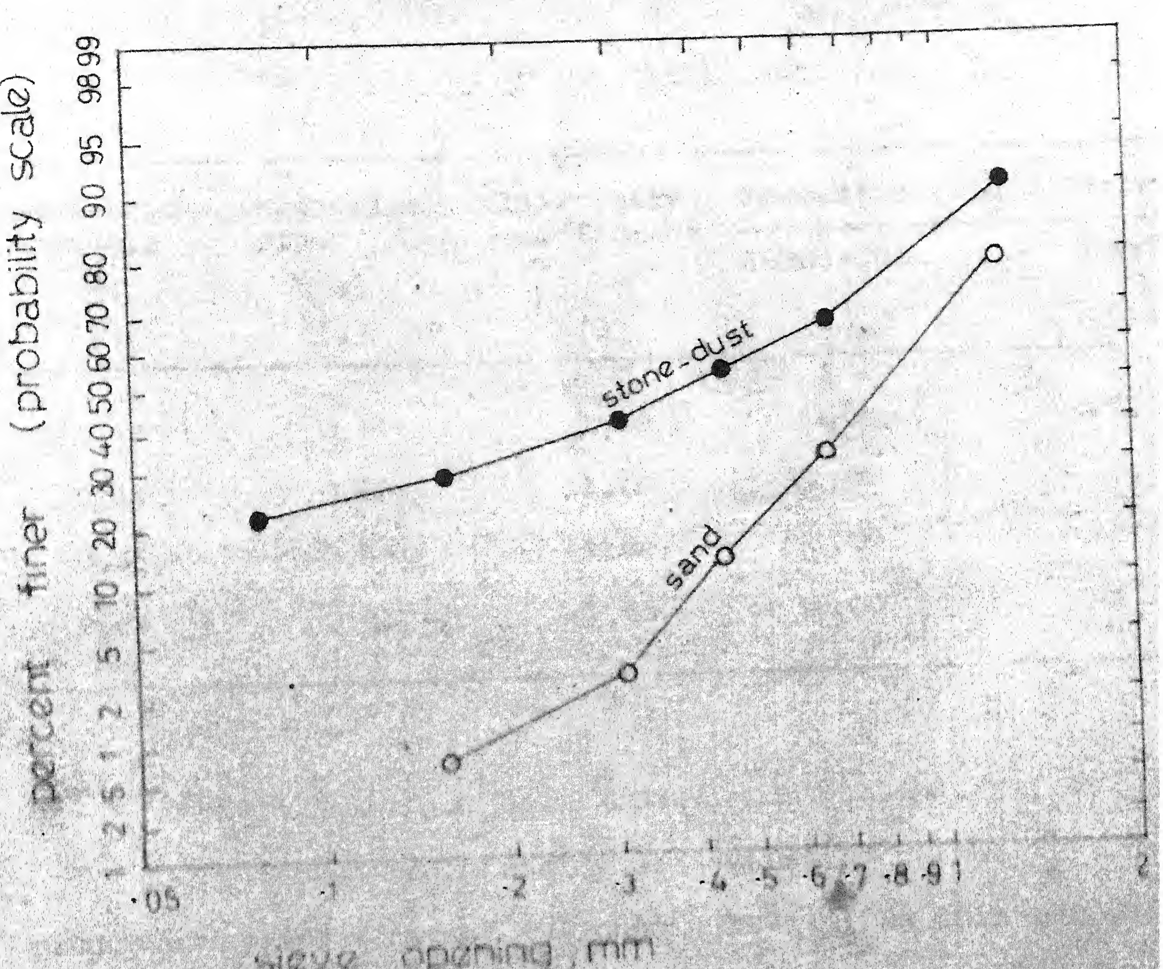


Figure 4.1 – Mechanical analysis of stone-dust and sand media

offset this provided the stone-dust satisfies the other requirements.

Table 4.1 - Percent usable material.

Geometric mean size mm (1)	Effective size mm (2)	Uniformity coefficient (3)	Percent usable material	
			Stone-dust (4)	sand (5)
0.46	0.44	1.09	10.00	13.00
0.54	0.53	1.09	12.00	15.00
0.65	0.62	1.04	13.00	18.00
0.84	0.63	1.55	31.00	74.00

4.3 Porosity

The packed bed porosity was estimated by the graduated cylinder method (O'Connor, 1975). In this method, a known volume of dry filter media was placed in a graduated cylinder containing a known volume of water. Condition of backwashing was simulated by inverting the cylinder number of times. The cylinder was then gently tapped so as to get a level surface of media. Porosity of the media was calculated as

Dry volume of media	(i)
Volume of water	(ii)
Volume of media after tapping	(iii)
Volume of media + water after tapping	(iv)

$$\text{Porosity} = \frac{(iii) - (iv) - (ii)}{(iii)} \tag{4.1}$$

The porosity values obtained for different sizes of the same media (stone-dust or sand) were almost same and, therefore, an average value is reported here and used in the work. Mean porosity values (12 observations) of the stone-dust and sand were found out to be 0.49 and 0.35, respectively. It remaines to be seen whether the higher value of porosity of the stone-dust is of any benefit in water filtration.

4.4 Specific gravity

For specific gravity determination, a standard pycnometer bottle was employed. The specific gravity values (mean of 8 observations) for the stone-dust and sand were 2.58 and 2.73, respectively. This indicates that the stone-dust has a lower specific gravity but not significantly different from that of sand. A lower value of specific gravity is presumably beneficial in backwashing operation.

4.5 Solubility test

The procedure for the solubility test consists of keeping a known mass of the dry media in contact with 10 percent (V/V) hydrochloric acid for 24 hr. After this

period, the sample was thoroughly washed with distilled water, dried at 103°C for 2 hr and weighed. The percent solubility value was determined from the loss in weight of the sample. The mean value of solubility (3 observations) for the stone-dust and sand were 4.67 and 3.05 percent, respectively indicating that the stone-dust media **is** within the recommended limit of 5 percent (Manual, 1976).

4.6 Sphericity

The sphericity of the media particle was found out from its settling characteristics. The mean time required for fall through a particular height of 8-10 media particles of known geometric mean size was observed in a tall glass column (50 mm ID). The observed settling velocity was employed to determine the value of $\frac{C_D}{R}$ in the equation (Camp, 1946)

$$\frac{C_D}{R} = \frac{4}{3} g \frac{\rho_s - \rho_w}{\rho_w^2} \frac{\mu}{v_s^3} \tag{4.2}$$

where, C_D = coefficient of drag,

R = Reynold's number, and

v_s = settling velocity of particle.

The value of R was found out from the curve of $\frac{C_D}{R}$ vs.R prepared using the relation $\frac{C_D}{R} = \frac{24}{R^2} + \frac{3}{R^{1.5}} + \frac{0.34}{R}$. Sphericity was obtained from the following relation

$$\Psi = \frac{R}{d_m} \times \frac{\mu}{v_s \rho_w} \tag{4.3}$$

where, ψ = sphericity.

Sphericity values for different sizes of the stone-dust and sand media are shown in Table 4.2.

Table 4.2 - Sphericity of stone-dust and sand media.

Geometric mean size mm (1)	Effective size mm (2)	Uniformity coefficient (3)	Sphericity	
			Stone-dust (4)	Sand (5)
0.46	0.44	1.09	0.87	0.91
0.54	0.53	1.09	0.84	0.88
0.65	0.62	1.04	0.81	0.85
0.84	0.63	1.55	0.73	0.77

4.7 Attrition test

This test measures the loss of material due to wear and tear of media with time. A continuous backwashing operation of 100 hr duration was used to estimate this value. This corresponds to 2 to 3 years' life of normal operation. A known amount of the filter media (150 g) was placed in a glass column (25 mm ID) and backwashed at 50 percent bed expansion for 100 hr. After this period, production of fines (less than 75 μm) was determined by sieving the dried media through a 200 mesh sieve (75 μm) and the attrition test value or dust production was computed based

on the material coarser than 75 μm and was expressed as percent of the initial material. Figure 4.2 shows attrition test values for the stone-dust with 30 and 50 percent bed expansion and sand with 50 percent bed expansion. The stone-dust media with 50 percent bed expansion has a higher attrition test values as compared to sand and the values exceed the recommended limit of 3 percent (Manual, 1976). The values with 30 percent bed expansion, however, are comparable to those with 50 percent bed expansion of sand. The media remaining after the attrition test sieving, i.e., retained on a 200 mesh sieve (75 μm) was subjected to another sieve analysis to assess the percent production of material finer than the original specification employed. The results are shown in Table 4.3. It is to be noted that dust production (Fig. 4.2) added to the percent finer values (Table 4.3) gives the total percent production of material finer than the original specification employed.

It is evident that both the media underwent reduction in size as a result of backwashing and this was more significant in the case of stone-dust. Formation of higher amount of finer material (a major fraction of which would remain in the filter with a smaller fraction escaping with backwash water) might result in a change in the filter coefficient and increase in headloss. The values of finer material formed with 30 percent bed expansion were low for stone-dust. Therefore, all attempts should be made to

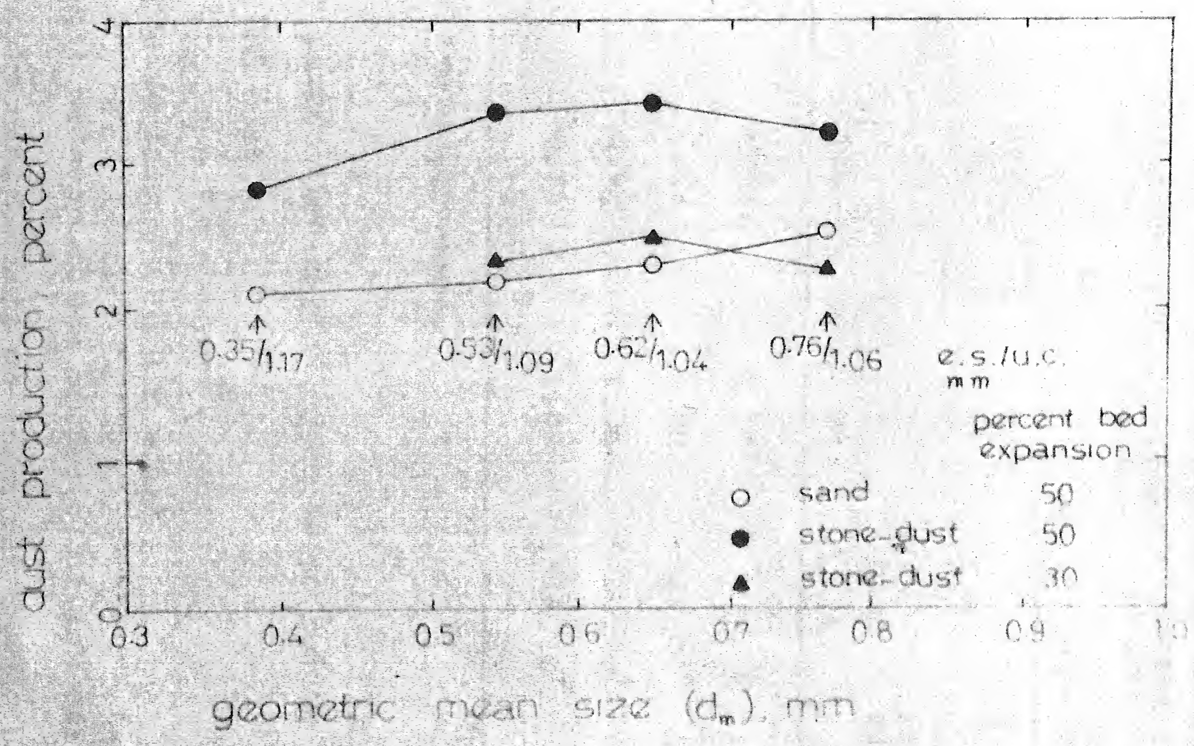


Figure 4.2 – Attrition test values for stone-dust and sand media

Table 4.3 - Percent of finer material after 100 hr backwashing.

Geometric mean size mm (1)	Effective size mm (2)	Uniformity coefficient (3)	Percent finer material after 100 hr backwashing: Stone-dust, 30 percent bed expansion (4)	Stone-dust, 50 percent bed expansion (5)	Sand, 50 percent bed expansion (6)
0.39	0.35	1.17	-	16.55	13.00+
0.54	0.53	1.09	15.00+	28.00+	22.30+
0.65	0.62	1.04	17.20+	-	-
0.78	0.76	1.06	16.20+	-	-

+ Mean of two observations.

limit the percent bed expansion so as to reduce the production of fines and dust.

4.8 Abrasive loss due to air scour

With widespread use of air scour for effective filter backwashing, effect of air scour on the stone-dust media is of concern as this media has a lower value of hardness compared to the value of sand (5 and 7, respectively on Mohs' scale). Hence an experiment was conducted to estimate the abrasive loss due to air scour. A 500 g sample of the filter media of geometric mean size of

0.77 mm (e.s. 0.65 mm; u.c. 1.43) was placed in a glass filter column (25 mm ID) containing water and subjected to air scour for 100 hr. The rate of air flow was not measured but was sufficient to fluidize the bed while preventing displacement of the coarser supporting layers. The water was replaced at intervals of 8 to 10 hr. At the end of operation, the abrasive loss was computed based on material remaining coarser than 75 μm and a sieve analysis was also done to estimate final media size (effective size and uniformity coefficient). The abrasive loss (percent production of material finer than 75 μm) for both the media is comparable (2.0 and 1.9 percent for the stone-dust and sand, respectively). The final media size is also comparable (e.s. 0.57 mm; u.c. 1.48).

4.9 Initial headloss

Headloss through both the media under clean bed condition was recorded at different filtration rates and media sizes, and headloss coefficient (headloss per unit depth expressed as a dimensionless parameter) vs. filtration rate is shown in Fig. 4.3. A lower headloss coefficient in case of stone-dust media indicates that it might be possible to get longer filter runs as a result of greater margin of headloss available for floc storage in the filter bed.

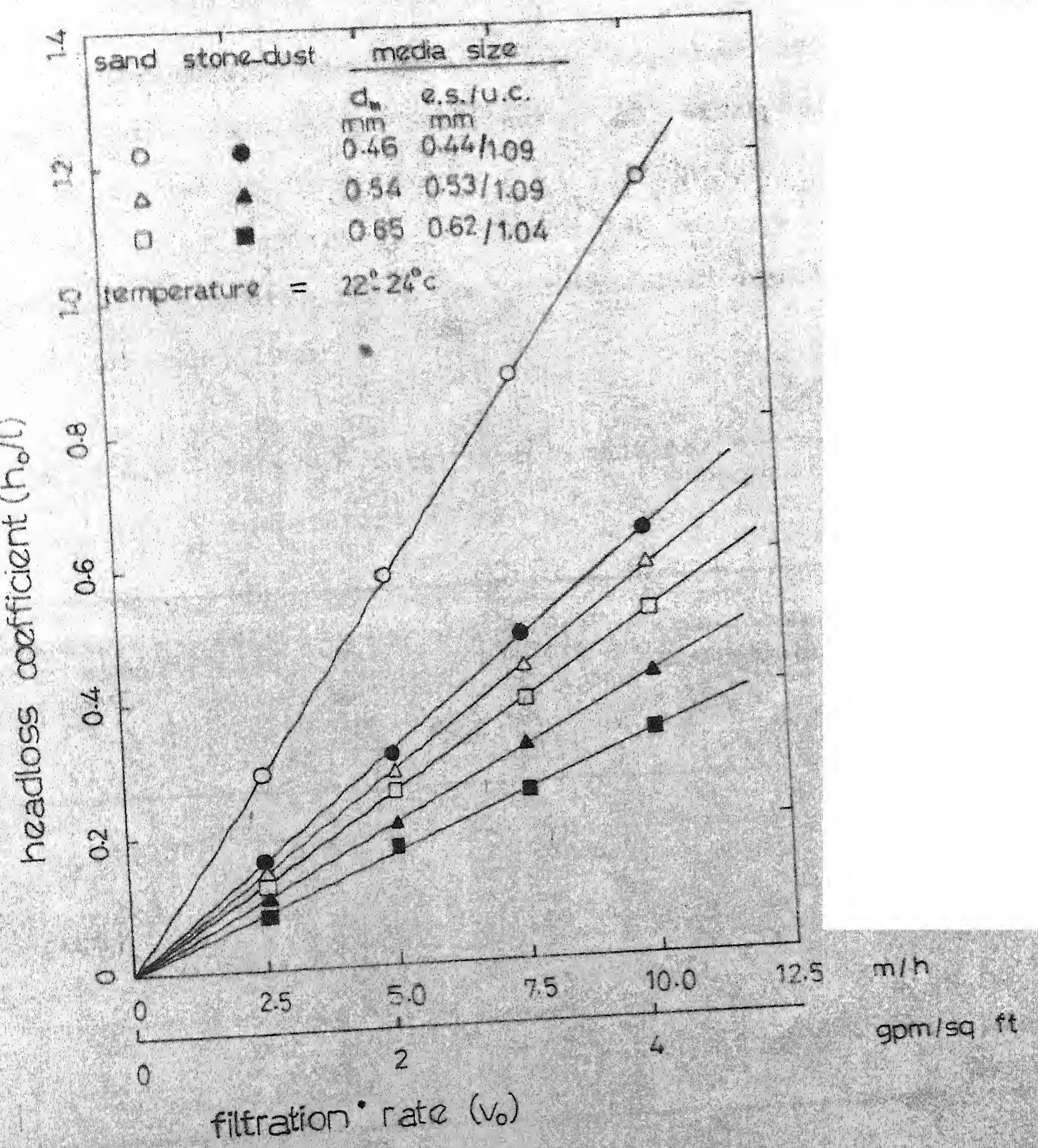


Figure 4.3 - Initial headloss for stone-dust and sand media

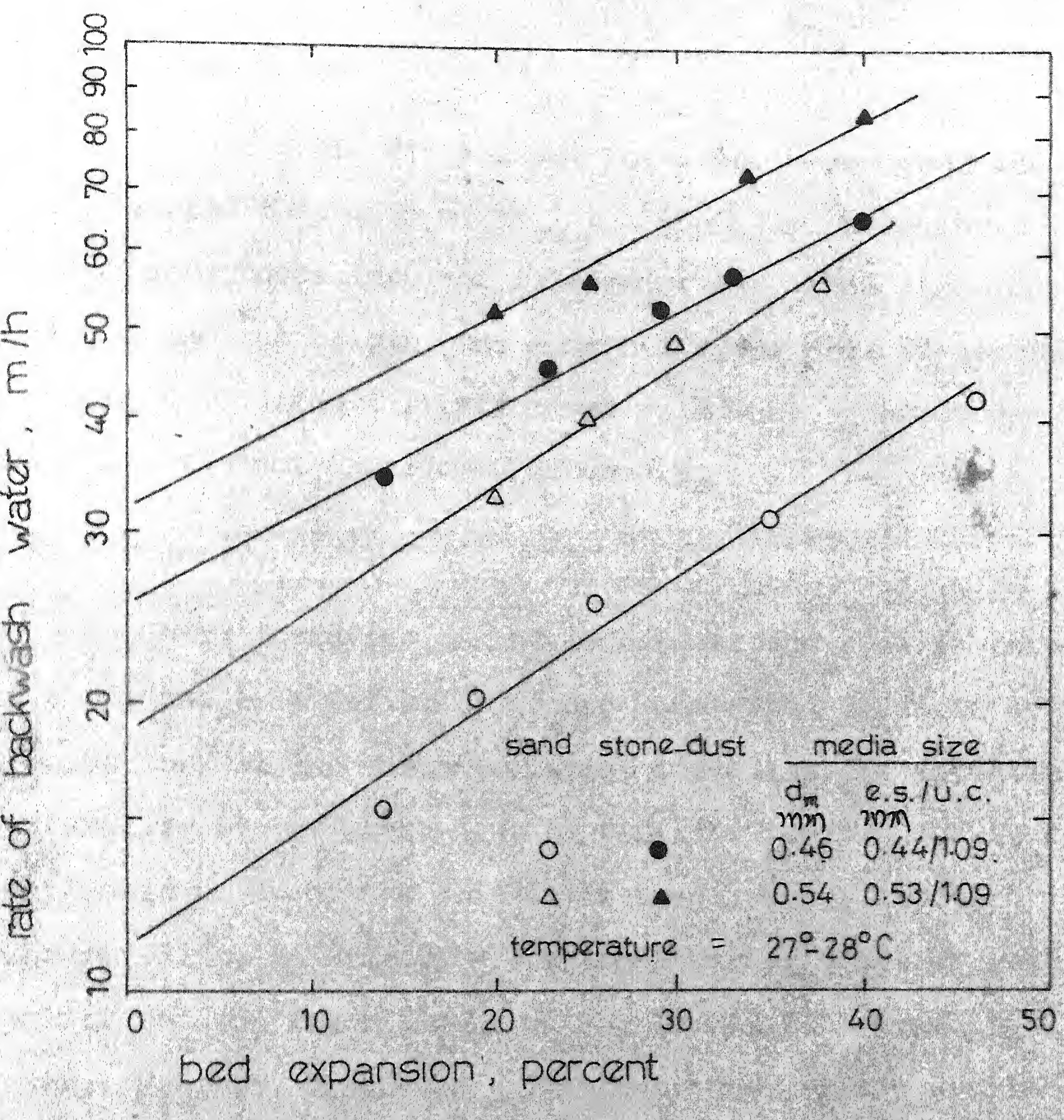


Figure 4.4 - Backwash water requirement for stone-dust and sand media

compared to 0.35). All attempts to minimize wash water requirement should be made, e.g., using auxiliary air scour for effective backwashing (Water Treatment Handbook, 1973).

4.11 Leaching test

This test is recommended for bitumineous coal where it is doubted that coal might leach phenolic and other organic substances into the filtered water. The stone-dust being of igneous origin, any possibility of organic matter leaching out during filtration was ruled out. Consequently, this test was not considered necessary.

4.12 Summary

Characteristics of the stone-dust and sand in terms of their use as a filter media are summarized in Table 4.5. A close look at the characteristics indicates the potential suitability of the stone-dust as a filter media. The stone-dust media no doubt has some limitations, e.g., greater susceptibility to attrition/abrasion, higher backwash water rate requirement and lower amount of usable material from the stack. However, considering its lower cost, ready availability, and low initial headloss coefficient, it should find application at places where sand has to be transported from a long distance. It would be appropriate, however, to conduct laboratory as well as pilot plant filtration experiments before making any definitive recommendation.

Table 4.5 - Characteristics of stone-dust and sand media.

Parameter		Stone-dust	Sand
Output of usable material, percent			
d_m, mm	e.s.(mm)/u.c.		
0.46	0.44/1.09	10.00	13.00
0.54	0.53/1.09	12.00	15.00
0.65	0.62/1.04	13.00	18.00
0.84	0.63/1.55	31.00	74.00
Porosity		0.49	0.35
Specific gravity		2.58	2.73
Solubility in hydrochloric acid, percent		4.67	3.05
Sphericity			
d_m, mm	e.s.(mm)/u.c.		
0.46	0.44/1.09	0.870	0.915
0.54	0.53/1.09	0.895	0.880
0.65	0.62/1.04	0.810	0.850
0.84	0.63/1.55	0.725	0.770
Attrition test value, percent			
d_m, mm	e.s.(mm)/u.c.		
0.46	0.44/1.09	3.05	2.20
0.54	0.53/1.09	3.40 (2.35)	2.25
0.65	0.62/1.04	3.50 (2.50)	2.30
(Values are for 50 percent bed expansion and those for 30 percent bed expansion are shown in parenthesis)			
Abrasive loss due to air scour, percent		2.00	1.90
Initial headloss coefficient at 5 m/h filtration rate			
d_m, mm	e.s.(mm)/u.c.		
0.46	0.44/1.09	0.32	0.57
0.54	0.53/1.09	0.21	0.32
0.65	0.62/1.04	0.16	0.26
0.84	0.63/1.55	0.22	0.42
Backwash water rate at 30 percent bed expansion, m/h			
d_m, mm	e.s.(mm)/u.c.		
0.46	0.44/1.09	43.0	26.0
0.54	0.53/1.09	52.0	40.0
0.65	0.62/1.04	71.0	49.0
0.84	0.63/1.55	91.0	56.0

5. LABORATORY FILTRATION EXPERIMENTS

Laboratory filtration experiments were conducted to investigate the performance of the stone-dust media in reference to sand with an additional objective of minimizing the variables for subsequent pilot plant studies.

5.1 Preparation of influent suspension

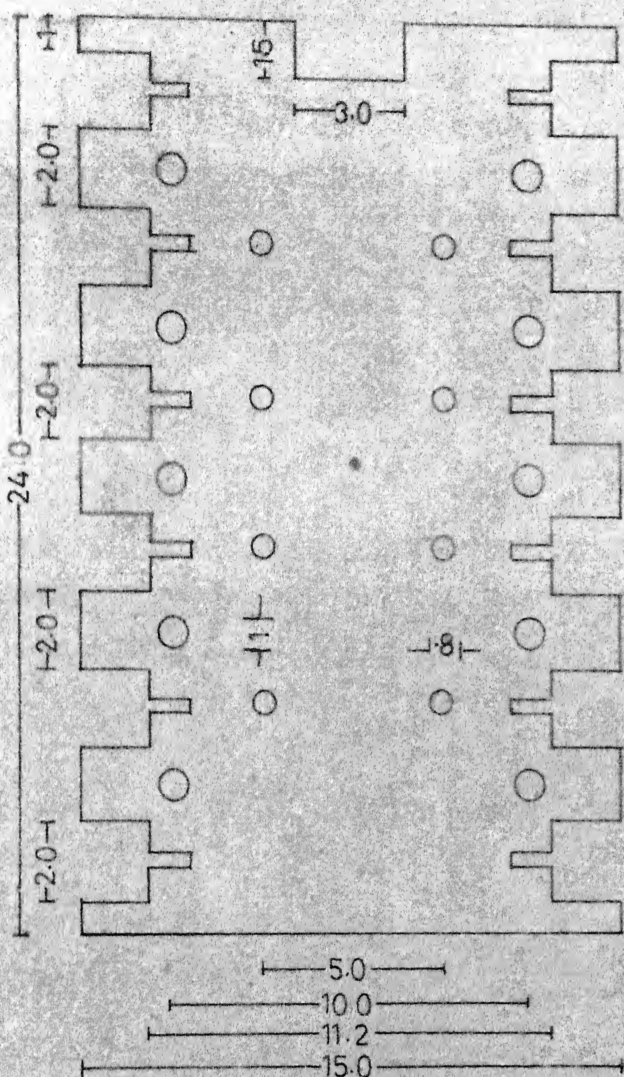
The influent suspension for all laboratory filtration experiments was a coagulated and settled water obtained through a batch alum (reagent grade Potash alum - $Al_2(SO_4)_3 \cdot K_2SO_4 \cdot 24H_2O$) coagulation of a "raw water" prepared in the laboratory using I.I.T., Kanpur tap water (Table 5.1) and lower Ganga canal sediment. X-ray data indicated predominance of kaolinite in the sediment.

Table 5.1 - Chemical analysis of I.I.T., Kanpur tap water

Constituents	Concentration, mg/l (except pH and conductance)
pH	7.8 - 8.2
Conductance	770 - 980 mhos/cm
Alkalinity (HCO_3^-)	440 - 450 (as $CaCO_3$)
Hardness	200 - 220 (as $CaCO_3$)
Calcium hardness	46 - 50 (as $CaCO_3$)
Magnesium hardness	154 - 170 (as $CaCO_3$)
Chlorides	20 - 21
Sulfates	24 - 25

In the procedure, about 10 g of the powdered (40 hr in a ball mill) sediment was soaked in 5 l of tap water for 8-10 hr followed by vigorous mixing for 2-3 min using a high speed laboratory stirrer. The suspension was then allowed to settle for 15 min to remove the readily settling particles and the supernatant was diluted with tap water to obtain a "raw water" of desired initial turbidity in the range of 60-65 NTU (measured in a model 2100A HACH turbidimeter).

This raw water was then batch coagulated in a 55 l plastic container employing a plastic flocculating paddle (Fig. 5.1) attached to a variable speed laboratory stirrer. A relationship between the alum dose and residual turbidity and batch coagulation conditions are shown in Fig. 5.2. An alum dose of 120-140 mg/l was adopted for preparation of the influent suspension which resulted in a residual turbidity in the range of 10-25 NTU. According to Shull (1967), flocs produced using the adopted dose are known to have good filterability. A microscopic examination of the influent suspension thus prepared indicated a floc size within the range of 15 μm. Floc density was estimated to be in the range of 1.22-1.26 using the sucrose solution method suggested by Lagvankar and Gemmel (1968). The cation exchange capacity of the clay (sediment) constituting turbidity of the raw water was observed to be in the range of 1.6-2.5 meq/100 g according to the methods suggested by Grim (1953) and Kim, Ludwig and Bishop (1965).



1 All dimensions in cm
2 Fixing holes not shown

Figure 5.1 - Flocculating paddle

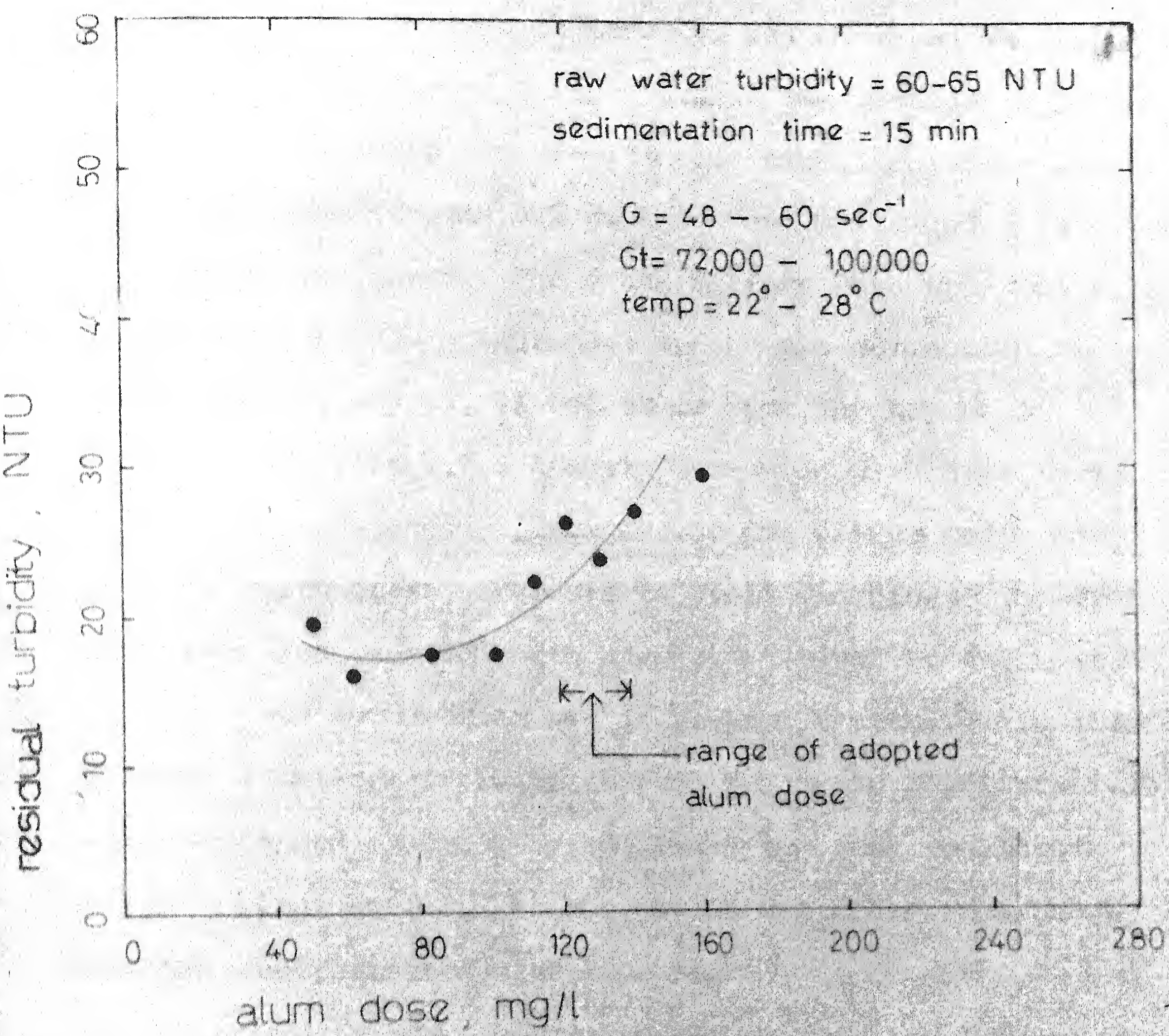


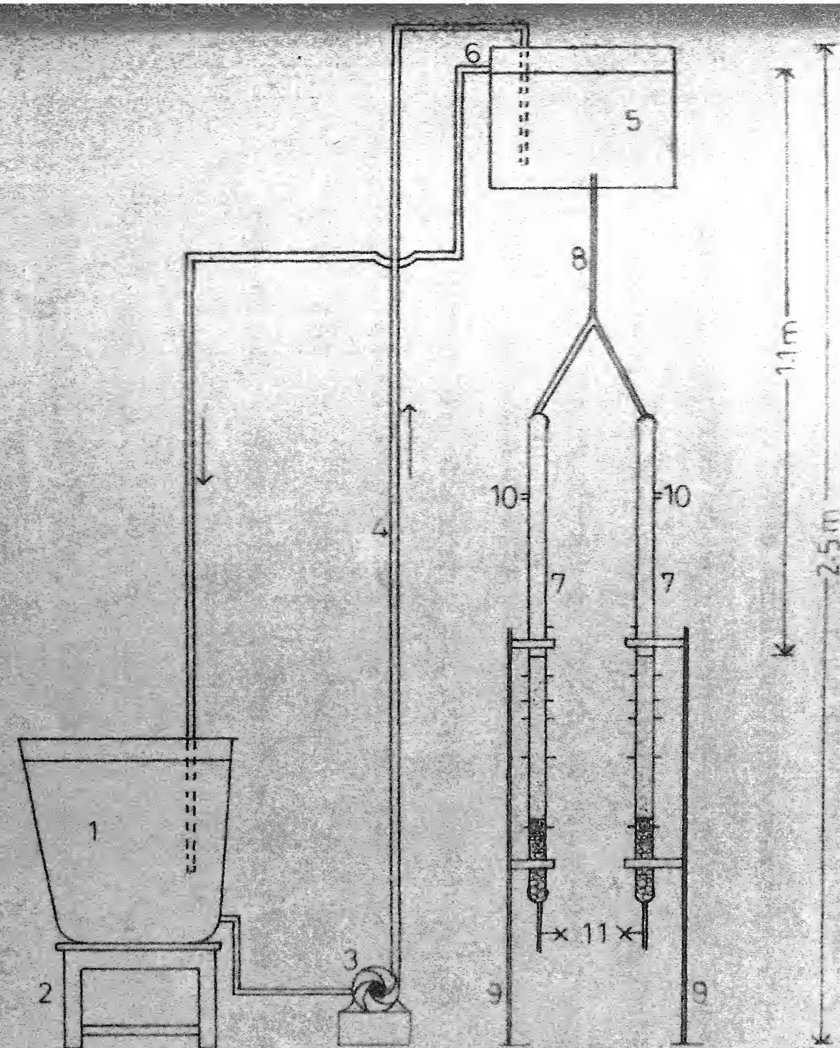
Figure 5.2 - Batch coagulation of the raw water

5.2 Laboratory filtration apparatus

A bench-scale filtration apparatus with two 25 mm ID glass filter columns in parallel was employed in all filtration experiments (Fig. 5.3). The parallel filter arrangement allowed for simultaneous experimentation using the stone-dust (68 cm) and sand (68 cm) media under identical operating conditions. The glass filters were provided with ports for headloss measurement and sample collection at depths of 11, 19, 29, 41 and 68 cm from the top of the media in the filter. The ports were made with capillary glass tubes projected 2.5 mm inside the filter media and provided with brass strainers to avoid clogging. The overhead tank was provided with a constant level arrangement using a pump and overflow-recirculation system. This also ensured a uniform influent suspension. Rate of filtration was maintained manually by adjusting the flow regulators at the filter outlet. At the end of the filter run, backwashing was performed with tap water.

5.3 Filterability number

The filterability number concept (Ives, 1978) as described in section 2.10 was applied for a preliminary assessment of the suitability of the stone-dust media in reference to sand. As originally proposed, this procedure allows for rapid screening of various pretreatments, media sizes and filtration rates, to reduce the number of tests



LEGEND

01	plastic container (55 l)
02	wooden stool
03	0.5 h.p. pump (350 l/h & 3 m head)
04	delivery pipe (8 mm)
05	overhead tank (15 l)
06	overflow - recirculation arrangement
07	glass filter column (25 mm ID)
08	inlet arrangement
09	stand for filter column
10	wash water outlet
11	flow regulator

(manometer board not shown)

Figure 5.3 - Laboratory filtration apparatus

required on experimental or pilot filters. In the present study, however, this was used more as a tool for a preliminary comparative evaluation of the stone-dust media in reference to sand. Filterability number was determined using several media depths (in contrast to 4 cm as originally recommended), media sizes and filtration rates to obtain some additional information, if possible, that could be made use of in subsequent laboratory filtration experiments.

5.3.1 Procedure

The filtration apparatus (Fig. 5.3) described in section 5.2 was employed for determination of filterability number. A 820 ml volume of the influent suspension (prepared according to the procedure described in section 5.1) was filtered through 68 cm depth of both the stone-dust and sand media and observations were made for headloss as well as influent and effluent turbidity (measured in a model 2100A HACH turbidimeter) at depths of 11, 19, 29, 41 and 68 cm from the top of media surface. Time for displacement of the clean water above and within the filter media was taken into consideration. Three media sizes (d_m 0.46 mm, e.s. 0.44 mm, u.c. 1.09; d_m 0.54 mm, e.s. 0.53 mm, u.c. 1.09; and d_m 0.65 mm, e.s. 0.62 mm, u.c. 1.04), three filtration rates (5.0, 7.5 and 10.0 m/h) and two influent turbidity levels (10 and 25 NTU) were employed for the determination of filterability number.

5.3.2 Results and discussion

Headloss and turbidity data (average of 3 observations for each set) for filterability number determination are presented in Appendix Tables A1 and A2 for stone-dust and sand, respectively. From these values, filterability number was computed (equation 2.18) and the values for the stone-dust and sand media are reported in Tables 5.2 and 5.3, respectively. For good filtration, i.e., good filterability, the numerator of equation 2.18 should be low, with a low headloss value (h) and low filtrate turbidity (c). Also, the denominator should be high, with a high filtration rate (V_o), accepting high influent turbidity (c_o) during a long time of operation. Consequently, good filterability is expressed by a low filterability number. Low filterability number values for the stone-dust media and comparable to those for the sand media in terms of the order of magnitude indicate the filtration suitability of the stone-dust media for alum coagulated suspension. A closer look at Tables 5.2 and 5.3 also brings out the fact that filterability number for the stone-dust media has a lower dependance on filtration rate indicating its potential advantage at high filtration rates. Inclusion of different media sizes and depths in filterability number determination did not provide any additional useful information.

Table 5.2 - Filterability number for stone-dust media

Media size	Filtration rate (V_o) m/h	Influent turbidity (c_o) NTU	Filterability number (x 10^{-3}) at indicated depths				
			11 cm	19 cm	29 cm	41 cm	68 cm
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	5.0	10.38	7.49	7.56	7.27	6.48	9.70
	7.5	10.40	10.09	12.22	12.65	16.33	13.38
d_m 0.46 mm	10.0	10.00	10.81	11.40	12.91	15.45	10.59
e.s. 0.44 mm	5.0	24.33	3.52	2.49	3.02	2.94	4.53
u.c. 1.09	7.5	25.50	3.51	2.97	2.74	3.23	3.91
	10.0	23.67	9.88	9.63	9.17	10.73	9.88
	5.0	9.88	4.28	4.09	5.15	5.59	4.95
	7.5	10.33	4.69	5.07	4.54	4.96	4.29
d_m 0.54 mm	10.0	10.50	9.81	9.52	12.78	18.29	11.78
e.s. 0.53 mm	5.0	24.33	3.65	2.78	3.04	3.71	4.05
u.c. 1.09	7.5	24.83	6.14	4.64	4.15	4.05	4.71
	10.0	24.67	12.54	10.20	8.44	6.32	7.22
	5.0	11.00	6.59	7.17	9.00	9.18	5.10
	7.5	10.42	6.68	7.87	6.73	7.18	6.17
d_m 0.65 mm	10.0	10.83	8.71	9.89	9.31	8.59	9.84
e.s. 0.62 mm	5.0	25.33	3.74	3.23	2.47	1.67	2.30
u.c. 1.04	7.5	25.17	6.26	5.46	5.44	3.28	3.36
	10.0	23.83	9.38	9.41	7.86	6.26	6.63

5.4 Laboratory filtration experiments

These were proposed to be carried out for the comparative evaluation of the stone-dust and sand media under parallel laboratory filtration experiments and identical conditions of media size, filtration rate and influent turbidity. Additional objectives were to obtain information on operational optima in terms of depth of filter media and length of filter run for a predetermined headloss limit and effluent turbidity criteria and comparative filtration behaviour of the two media in terms of filter coefficient and specific deposit.

5.4.1 Procedure

All laboratory filtration experiments were conducted with alum coagulated and settled water (prepared according to procedure described in section 5.1) and with operational variables (media size, filtration rate and influent turbidity) as outlined in section 5.3.1. The stone-dust or sand media of a specified size once placed in a filter was replaced only when experimentation with a different media size was to be initiated and the first two filter runs were made for conditioning of the bed and no observations were taken during this period. All the filter runs were made in triplicate.

During a filter run, at predetermined time intervals headloss observations at various depths were taken first and

this was followed by collecting a 25 ml sample for turbidity measurement using an approximate flow rate not exceeding 2 ml/min and wasting the first few ml. A model 2100A HACH turbidimeter was employed for the turbidity measurement. The duration of a filter run was limited to 12 hr or less if the headloss limit of 1.7-1.8 m had occurred earlier. Both the stone-dust and sand filter runs were terminated when the criterion was reached for either of the two and always it was the sand filter. All the filtration experiments were performed in a temperature range of 22-26°C. Backwashing at the termination of a filter run was accomplished using tap water and 35-40 percent bed expansion. A backwashed filter was ready for use in subsequent filtration experiments.

5.4.2 Results and discussion

Headloss and turbidity data for the stone-dust and sand filters of three different media sizes at three different filtration rates employing 10 and 25 NTU (average) influent turbidity values are included in Appendix Tables B1-B3 and C1-C3. Plots of temporal headloss and quality variation (effluent influent turbidity ratio expressed as c/c_o) were made for all combinations (total eighteen) of media size, filtration rate and influent turbidity employed. Figures 5.4 to 5.7 show typical plots of the stone-dust and sand media for one combination(d_m 0.46 mm, e.s. 0.44 mm, u.c. 1.09; V_o 10 m/h; and c_o 25 NTU). In these plots average values

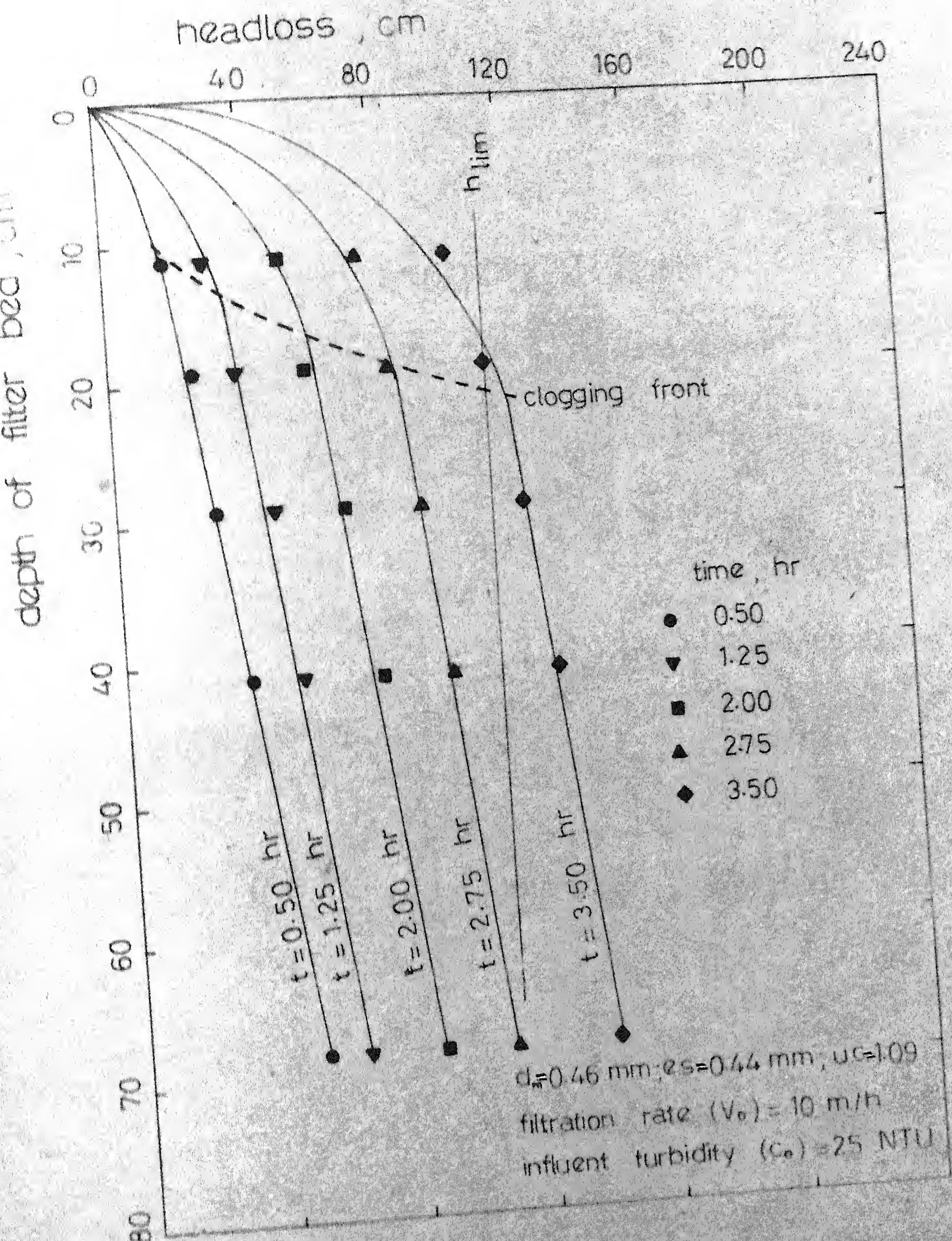


Figure 5.4 – Temporal headloss variation in filter bed in a stone-dust laboratory filter

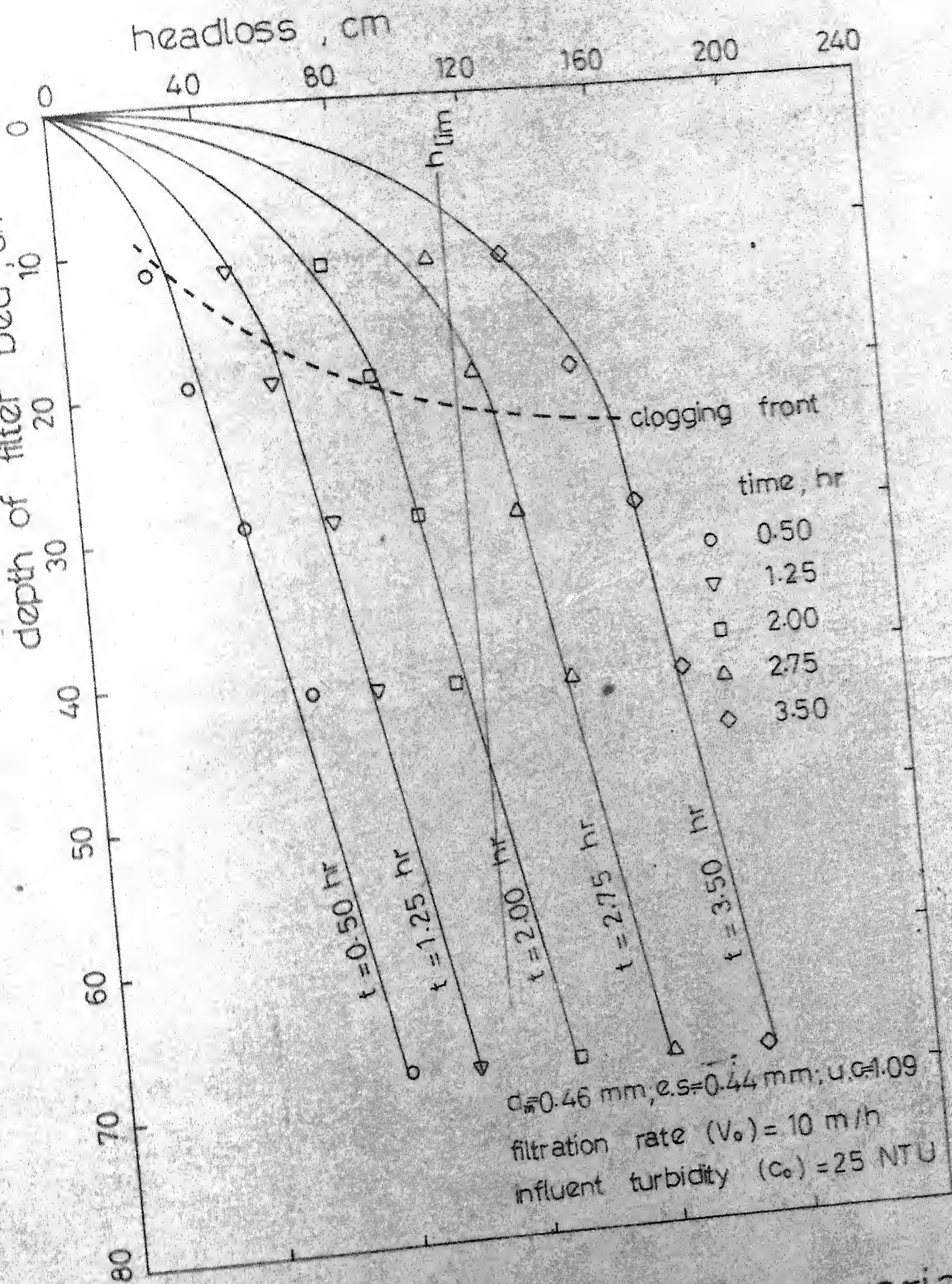


Figure 5.5 - Temporal headloss variation in filter bed in a sand laboratory filter

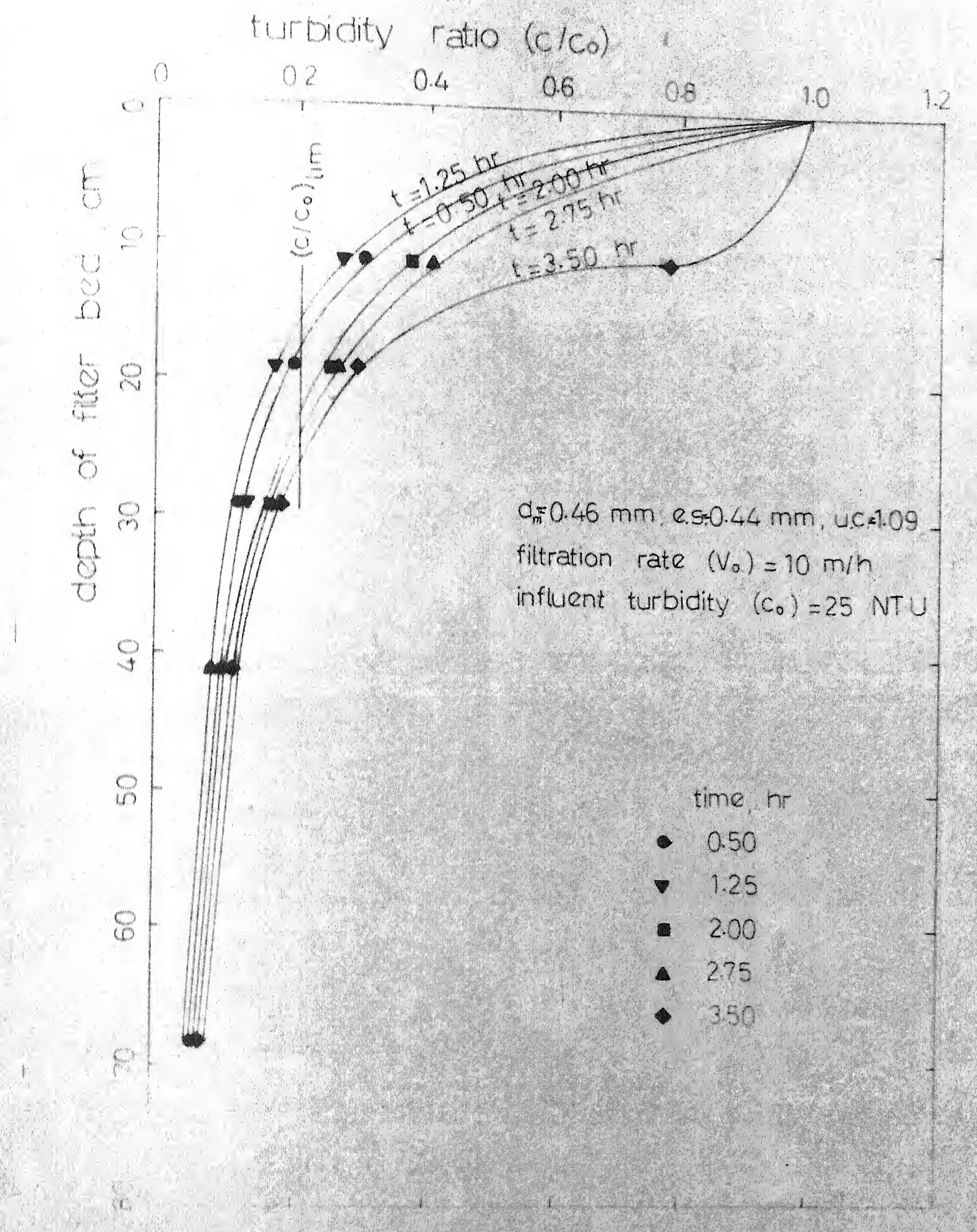


Figure 5.6 – Temporal quality variation in filter bed in a stone-dust laboratory filter

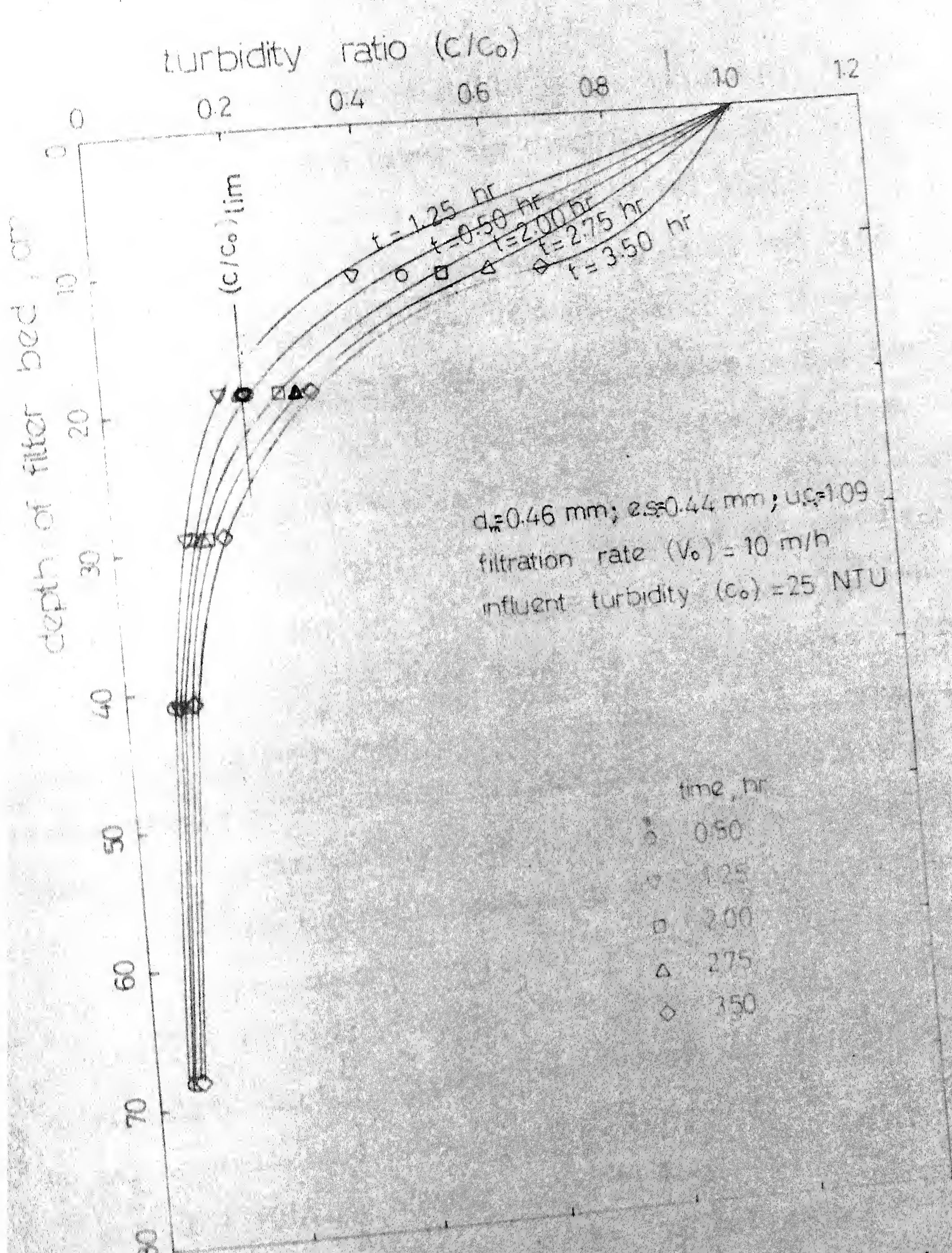


Figure 5.7 – Temporal quality variation in filter bed in a sand laboratory filter

of turbidity ratio and headloss of the triplicate filter runs (Appendix Tables B1-B3 and C1-C3) were used.

5.4.2.1 General performance of the media

A close look at the headloss and effluent quality (turbidity) data for the stone-dust and sand filters indicates that with the stone-dust media headloss values were lower at the same time effluent quality was comparable to that obtained in the sand filter. Thus, with the stone-dust as a filter media, it may be possible to obtain longer filter runs, reduce the frequency of backwashing and thereby producing greater output of filtered water. This is in accordance with the recent observations of Trussell and others (1980) based on plant performance data that angular filter media provides more satisfactory performance.

Both the media behaved in a similar manner in terms of turbidity removal. Majority of the turbidity removal occurred in a small depth at the surface. The effluent turbidity during a filter run improved in the initial stage and deteriorated gradually thereafter but the value at the end of a run was always less than 2 NTU which is within the prescribed limit (Manual, 1976). No turbidity breakthrough (sudden deterioration of effluent turbidity) was observed in case of those filter runs which were terminated before 12 hr on the basis of headloss limit criterion. This substantiates the well known dictum that where headloss limit

governs the filter run the risk of turbidity breakthrough is minimized.

5.4.2.2 Operational optimization

The concept of operational optimum (section 2.8) was applied to estimate filter bed depth and time of operation (length of filter run) for all combinations of media size, filtration rate and influent turbidity employed in the laboratory filtration experiments. The graphical method using the concept by Mintz (1966) was followed. An arbitrary headloss limit criterion (h_{lim}) of 1.1 m (dictated by the water depth above the media surface so as to avoid negative pressure in the filter) and a turbidity ratio criterion($(c/c_o)_{lim}$) of 0.20 were adopted for estimating the operational optimum. Filter bed depths required for reaching the above criteria at various times during a filter run were read from the temporal plots of quality variation (turbidity ratio) and headloss and plots were made for all combinations of media size, filtration rate and influent turbidity. A typical of the eighteen plots is shown in Fig. 5.8. Point of intersection of the headloss limit (h_{lim}) and turbidity ratio (c/c_o lim) curves indicated operational optimum in terms of depth of filter bed (L_{opt}) and length of filter run (t_{opt}). Table 5.4 summarizes the results for the stone-dust and sand media.

The tedious exercise of estimation of operational optimum using the graphical method produced interesting

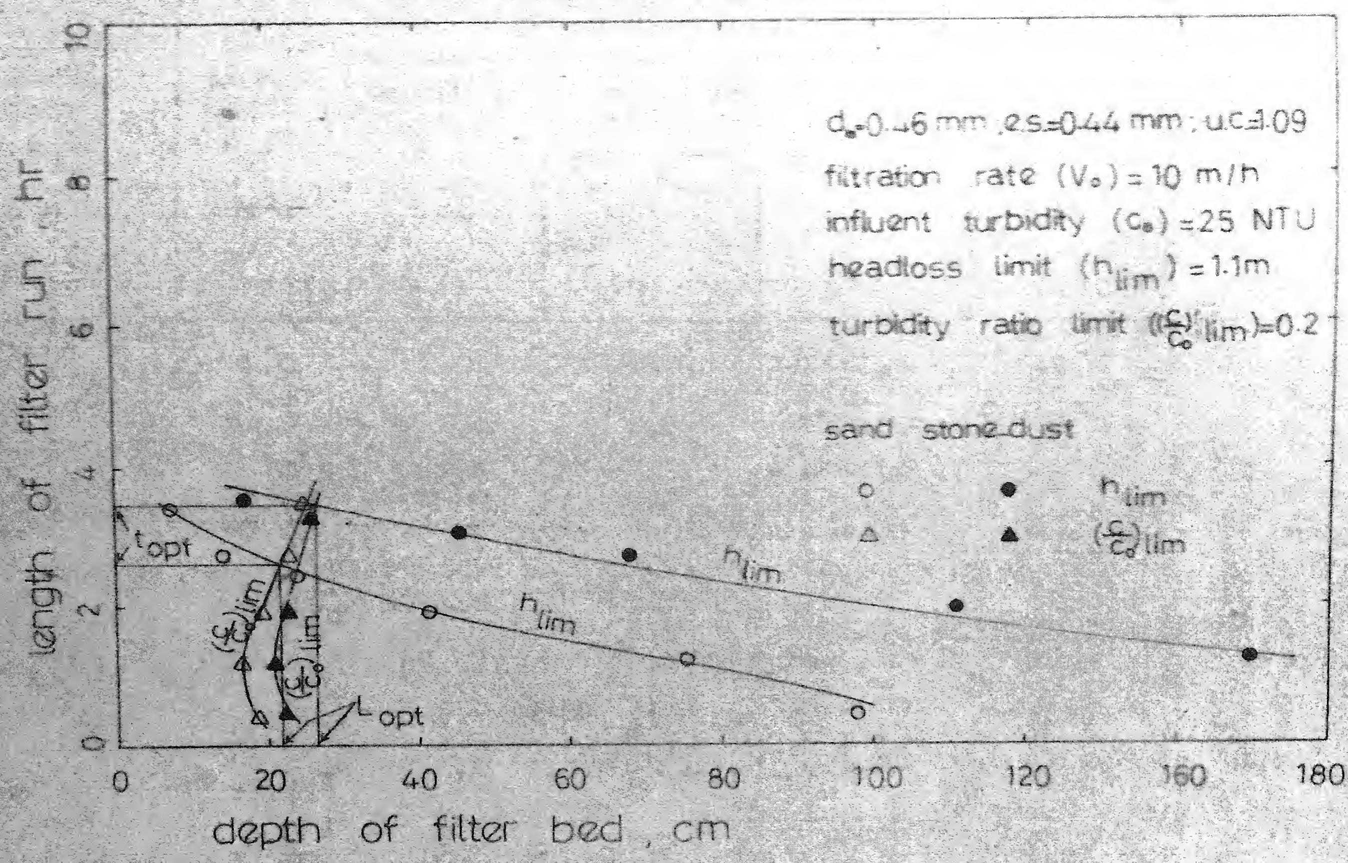


Figure 5.8 – Operational optimum for stone-dust and sand media

Table 5.4 - Operational optima for stone-dust and sand media

Media size	Influent turbidity (c_o) NTU	Filtration rate (V_o) m/h	Stone-dust media: Depth of filter bed (L_{opt}) cm	Stone-dust media: Length of filter run (t_{opt}) hr	Stone-dust media: Output of filtered water*	Sand media: Depth of filter bed (L_{opt}) cm	Sand media: Length of filter run (t_{opt}) hr	Sand media: Output of filtered water*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
d_m 0.46 mm	10	5.0	28.0	14.8	264.30	18.0	10.4	288.90
e.s. 0.44 mm		7.5	38.0	12.6	248.70	36.0	8.8	183.33
u.c. 1.09		10.0	53.0	6.5	122.60	38.0	4.6	121.00
	25	5.0	29.0	7.8	134.50	21.5	6.2	145.35
		7.5	29.0	4.6	119.00	27.0	3.2	88.90
		10.0	26.0	3.5	134.50	21.6	2.6	121.00
d_m 0.54 mm	10	5.0	53.0	19.5	195.00	62.0	15.2	122.58
e.s. 0.53 mm		7.5	32.0	16.5	269.50	48.0	9.8	175.90
u.c. 1.09		10.0	42.5	11.5	388.20	29.0	6.8	204.20
	25	5.0	26.0	7.6	147.10	26.0	4.8	92.30
		7.5	32.0	8.2	193.40	30.5	5.4	132.80
		10.0	33.0	6.2	187.90	31.0	4.1	132.20
d_m 0.65 mm	10	5.0	35.0	23.4	334.30	35.0	20.0	285.70
e.s. 0.62 mm		7.5	35.0	14.3	306.45	37.5	11.5	230.00
u.c. 1.04		10.0	38.3	12.0	313.70	35.0	10.7	305.00
	25	5.0	21.0	7.7	183.30	26.5	6.8	128.30
		7.5	30.0	6.7	167.50	32.0	5.3	124.20
		10.0	30.0	4.7	156.70	32.0	4.1	128.10

* Computed as total output of the filtered water (cu m) per cu m of filter bed employing the indicated operational optima (filter bed depth and length of filter run).

observations some of which could be used to advantage in subsequent pilot plant studies. However, it needs to be pointed out here that the objective of this exercise was not to cut down on the traditional filter media depth (usually 75 cm) where time to reach turbidity breakthrough is significantly longer than the time to reach limiting headloss, thus minimizing the risk of breakthrough if the filter is backwashed at a predetermined headloss. The significant observations based on the estimated operational optima (depth of filter bed and length of filter run) shown in Table 5.4 are

(1) In general, a filter bed depth of about 50 percent of the tradition depth of 75 cm was utilized when both headloss and effluent turbidity criteria limited the filter run.

(2) Increase in influent turbidity reduced the length of filter run as well as filter bed depth utilization indicating careful control of pretreatment.

(3) For both the stone-dust and sand media, and an average influent turbidity of 10 NTU, the coarsest media employed (d_m 0.65 mm, e.s. 0.62 mm, u.c. 1.04) showed most economical performance as evidenced by the output of filtered water per unit filter bed volume.

(4) Under identical operational conditions in terms of media size, filtration rate and influent turbidity, the stone-dust media produced longer filter runs.

The observation that for both the stone-dust and sand filters, the coarsest media specification showed most economical performance was made use of in subsequent pilot plant studies.

5.4.2.3 Clean bed filter coefficient

Filter coefficient is a measure of the efficiency of filtration. For filters employing two different filter media and operating under otherwise identical conditions, clean bed filter coefficient (λ_o), i.e., filter coefficient when the filter bed has just hydraulically stabilized and is not appreciably clogged, should presumably bring out the difference, if any, in terms of their intrinsic properties in the removal of particulate matter. The filter coefficient, at a later stage during the filter run when the filter bed has clogged appreciably, is additionally influenced by the previously deposited particles. In the present work, clean bed filter coefficient values were computed for 11 cm and 19 cm depths from the top surface employing fifteen min filtration data (Appendix Tables A1 and A2) for the stone-dust and sand media (Table 5.5) using the relationship.

$$\lambda_o = \frac{2.3 \log(c/c_o)}{L} \qquad 5.2$$

It is apparent from Table 5.5 that the clean bed filter coefficient values for the stone-dust and sand media are

Table 5.5 - Clean bed filter coefficient (λ_o) for stone-dust and sand media

Bed depth	Influent turbidity (c_o)	λ_o at indicated ψd_m and filtration rate, cm^{-1}							
		Stone-dust				Sand			
		ψd_m	5.0 m/h	7.5 m/h	10.0 m/h	ψd_m	5.0 m/h	7.5 m/h	10.0 m/h
cm	NTU	mm				mm			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
11	10	0.39	0.13	0.12	0.16	0.40	0.13	0.11	0.16
19	10	0.39	0.09	0.08	0.11	0.41	0.08	0.08	0.11
11	25	0.39	0.20	0.22	0.18	0.40	0.17	0.20	0.14
19	25	0.39	0.17	0.15	0.12	0.41	0.11	0.14	0.09
11	10	0.44	0.14	0.17	0.15	0.45	0.16	0.14	0.12
19	10	0.45	0.10	0.11	0.11	0.47	0.10	0.12	0.09
11	25	0.44	0.17	0.16	0.12	0.45	0.14	0.14	0.09
19	25	0.45	0.13	0.12	0.10	0.47	0.10	0.10	0.09
11	10	0.51	0.11	0.14	0.14	0.54	0.10	0.15	0.11
19	10	0.52	0.08	0.10	0.09	0.55	0.09	0.08	0.10
11	25	0.51	0.17	0.15	0.13	0.54	0.17	0.16	0.11
19	25	0.52	0.12	0.11	0.10	0.55	0.08	0.12	0.12

fairly comparable under identical filtration conditions. In general, the stone-dust filter exhibited slightly higher values. Apparently, the two media are comparable in terms of their intrinsic turbidity removal efficiency. Since the filter coefficient of a filter under clogging conditions during a filter run is dependent on the magnitude of the clean bed filter coefficient apart from other factors, it is reasonable to expect on the basis of the limited data that the performance of the stone-dust filter would be atleast comparable to the sand filter. As a matter of fact this is borne out by general filtration performance of the two media in terms of turbidity removal (Appendix Tables B1-B3 and C1-C3).

In order to further understand the relative influence of the relevant filtration parameters on the clean bed filter coefficient, an objective function was formulated relating filter coefficient (λ_o) to $\psi\, d_m$ (product of sphericity and geometric mean size of media), filtration rate (V_o) and influent turbidity (c_o). The data for the two media were processed using a digital computer and based on the relative values of the exponents (addendum, P. 141a), certain generalizations may be made, e.g., under clean bed conditions the efficiency of the stone-dust filter is less sensitive to fluctuations in influent turbidity and filtration rate but is more dependent on $\psi\, d_m$.

5.4.2.4 Specific deposit

Specific deposit values at different times during a filter run for the stone-dust and sand filters were computed for all the filter runs reported in Appendix Tables B1-B3 and C1-C3. The top 11 cm depth of the filter bed was considered since this happened to be the minimum depth of bed from top for which data were available (the first sampling port being at that depth). Also, from the general nature of the turbidity removal pattern it was apparent that this depth would give specific deposit values that would be significant for comparison purposes. Any depth greater than the considered depth would give lower values. The computed values were plotted against the corresponding filter coefficients. A typical of the eighteen plots prepared is shown in Fig. 5.9. Such plots exhibit the relative dependency of filter coefficient on specific deposit. These plots were also utilized to estimate the ultimate specific deposit values (specific deposit when the filter coefficient approaches zero) for the two media to ascertain their relative capacity for storage of particular matter (turbidity) during a filter run.

For determination of specific deposit an approach similar to the one used by Hudson (1969) and modified later by Bhunia (1979) was employed. This involved porosity change of the filter bed depicted by the Kozeny-Fair-Hatch equation (Fair and Hatch, 1933)

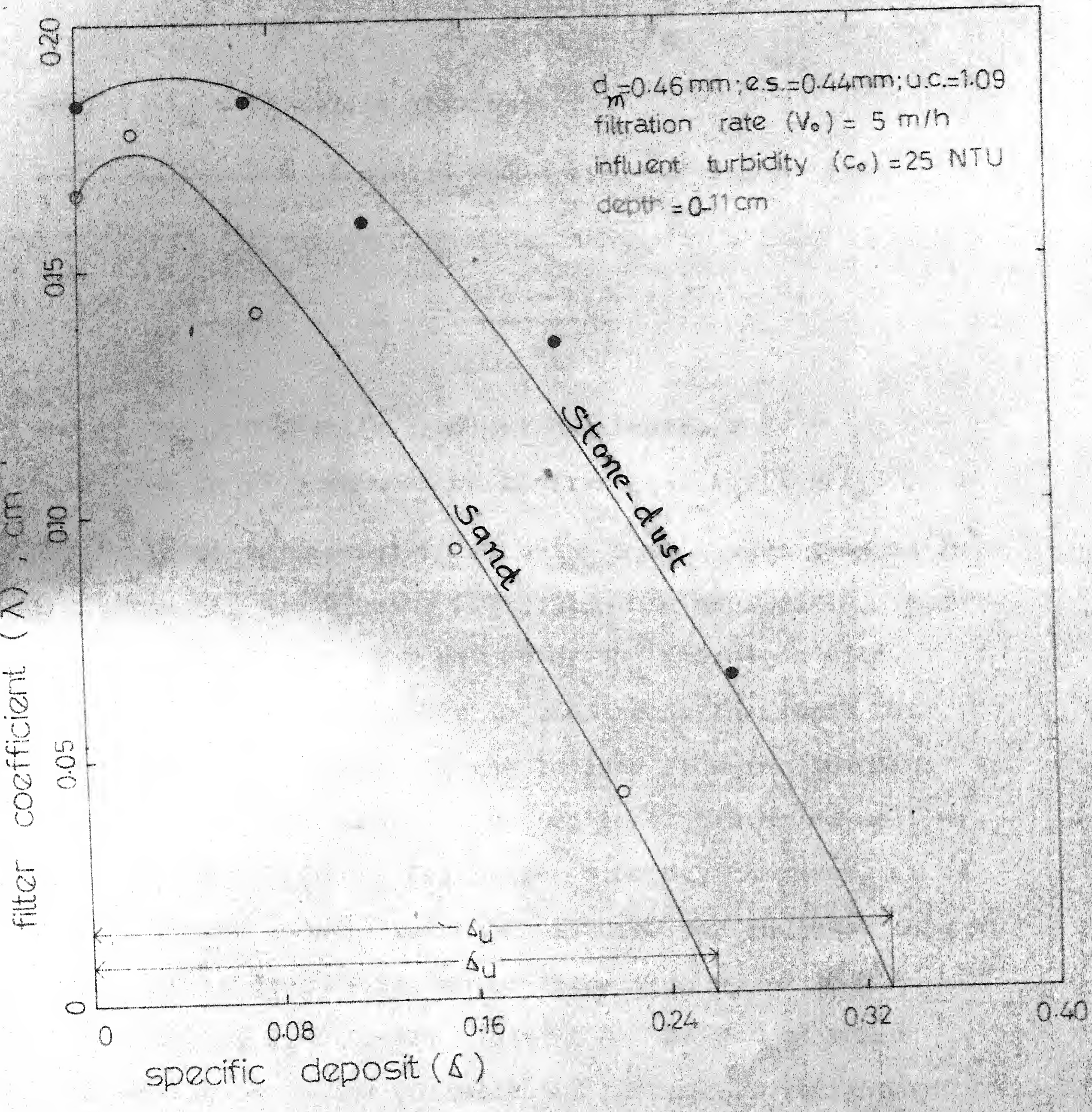


Figure. 5.9 – Filter coefficient versus specific deposit for stone-dust and sand media

$$i_o = j \frac{s_o^2}{g} \frac{(1 - f_o)^2}{f_o^3} \frac{v_o}{d_m^2} \quad 5.3$$

where, i_o = hydraulic gradient.

For a filter bed of stated media size and for a fixed filtration rate

$$\frac{i_t}{i_o} = \frac{K(1 - f_t)^2}{f_t^3} \quad 5.4$$

where, i_t = hydraulic gradient at time t, and

K = proportionality constant = $f_o^3/(1 - f_o)^2$.

The implicit assumption in equation 5.4 is that changes in the terms js_o^2 and d_m^2 with filtration are negligible. According to Camp (1964), the values of js_o^2 increases with increase in Reynolds number in the transition range but remain fairly constant in the laminar flow region which holds good in the case of a conventional filter as well as the present laboratory filtration studies. However, since change in the term d_m^2 is not considered any increase in the filter media grain size due to deposition would lead to estimation of f_t slightly higher than the actual value. Knowing the clean bed porosity and hydraulic gradient values (Appendix Tables B1-B3 and C1-C3, and Fig. 4.3) filter bed porosity at time t was computed from the equation 5.4. The volume of floc deposited in the filter bed was given by $(f_t - f_o)$ x (filter bed volume from top upto the depth of floc penetration). The depth of floc penetration (clogging

front distance from the top of filter bed) was obtained from the plot of headloss vs. depth of filter bed with time (Fig. 5.4 and 5.5). The specific deposit in the filter bed depth under consideration (0-11 cm from top) at any time t was given by the expression

$$\frac{(f_t - f_o) \times (\text{filter bed volume from top upto the depth of floc penetration})}{\text{filter bed volume for the considered depth}} \qquad 5.5$$

Variation of filter coefficient with specific deposit for both the media was found to follow a trend predicted by equation 2.11 proposed by Ives (1960), i.e., initial ripening followed by a gradual deterioration. However, in the case of the stone-dust filter values of the filter coefficient for the same specific deposit values were always higher under identical conditions of operation. This would indicate a presumably greater storage capacity for turbidity. For further assessment, the ultimate specific deposit values for all combinations of media size, filtration rate and influent turbidity were estimated and tabulated (Table 5.6).

The data in Table 5.6 indicate significantly higher values for the stone-dust filter under all conditions of operation and hence higher storage capacity for turbidity.

Table 5.6 - Ultimate specific deposit values for stone-dust and sand media

Influent turbidity (c_o) NTU	Media size			Ultimate specific deposit at indicated filtration rates					
				Stone-dust			Sand		
	d_m mm	e.s. mm	u.c.	5.0 m/h	7.5 m/h	10.0 m/h	5.0 m/h	7.5 m/h	10.0 m/h
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
10	0.46	0.44	1.09	0.30	0.27	0.24	0.24	0.21	0.19
	0.54	0.53	1.09	0.26	0.28	0.24	0.20	0.21	0.18
	0.65	0.62	1.04	0.28	0.26	0.24	0.18	0.17	0.16
25	0.46	0.44	1.09	0.33	0.29	0.26	0.26	0.21	0.18
	0.54	0.53	1.09	0.29	0.28	0.27	0.25	0.20	0.18
	0.65	0.62	1.04	0.28	0.26	0.24	0.22	0.19	0.18

5.5 Summary

The laboratory filtration experiments indicated in general the suitability of the proposed stone-dust filter for alum coagulated turbid water. The data also indicated certain operational advantages of the stone-dust filter over the traditional sand filter, e.g., greater turbidity storage capacity and longer filter runs with comparable effluent turbidity. The intrinsic turbidity removal capacity of the stone-dust media was also observed to be comparable to that of sand. It was logical at this stage to confirm some of the significant observations through a pilot plant study under a real-world situation.

6. PILOT PLANT STUDIES

The pilot plant studies, employing the proposed stone-dust and the traditional sand media, were conducted at the Laxminarayana Giri Water Treatment Plant, Bhopal as the specific problem pertained to this region of the country. As outlined earlier, the major objective was an engineering demonstration of the applicability of the stone-dust filter using a real-world situation. This phase of the study was designed to confirm some of the significant observations of the laboratory filtration experiments, e.g., predicted operational advantage of the stone-dust filter over the traditional sand filter in terms of longer filter runs with comparable effluent quality. Additionally, performance data for both the stone-dust and sand filters was collected under various filtration practices, e.g., constant rate, declining rate and direct filtration.

6.1 Brief description of the Laxminarayana Giri Water Treatment Plant, Bhopal

A 22.5 mld (5.93 mgd) capacity water treatment plant for the capital project area of Bhopal is located at Laxminarayana Giri, Bhopal. The plant draws raw water from the upper lake which is 5 km away from the treatment plant. This lake also serves as a source of raw water for other nine water treatment plants of the city. The total installed capacity of all the treatment plants is 127.5 mld (33.7 mgd).

The catchment area of the lake is 370 sq km and its water spread area at full level is 32.1 sq km. The storage capacity of the lake is 88.3 x 10^6 cu m and this corresponds to an average annual rainfall of 75 to 80 cm. Proposals for getting raw water from other sources is presently under consideration. This lake receives a number of a drains carrying sullage of the city. It has been reported that about 12.5 percent of city population live in the area sloping towards the lake (Aboo, and Manuel, 1967). The Madhya Pradesh Public Health Engineering Department has taken measures for rehabilitation of the population; however, the quality of the lake water is still subject to the influence of varying degrees of pollution.

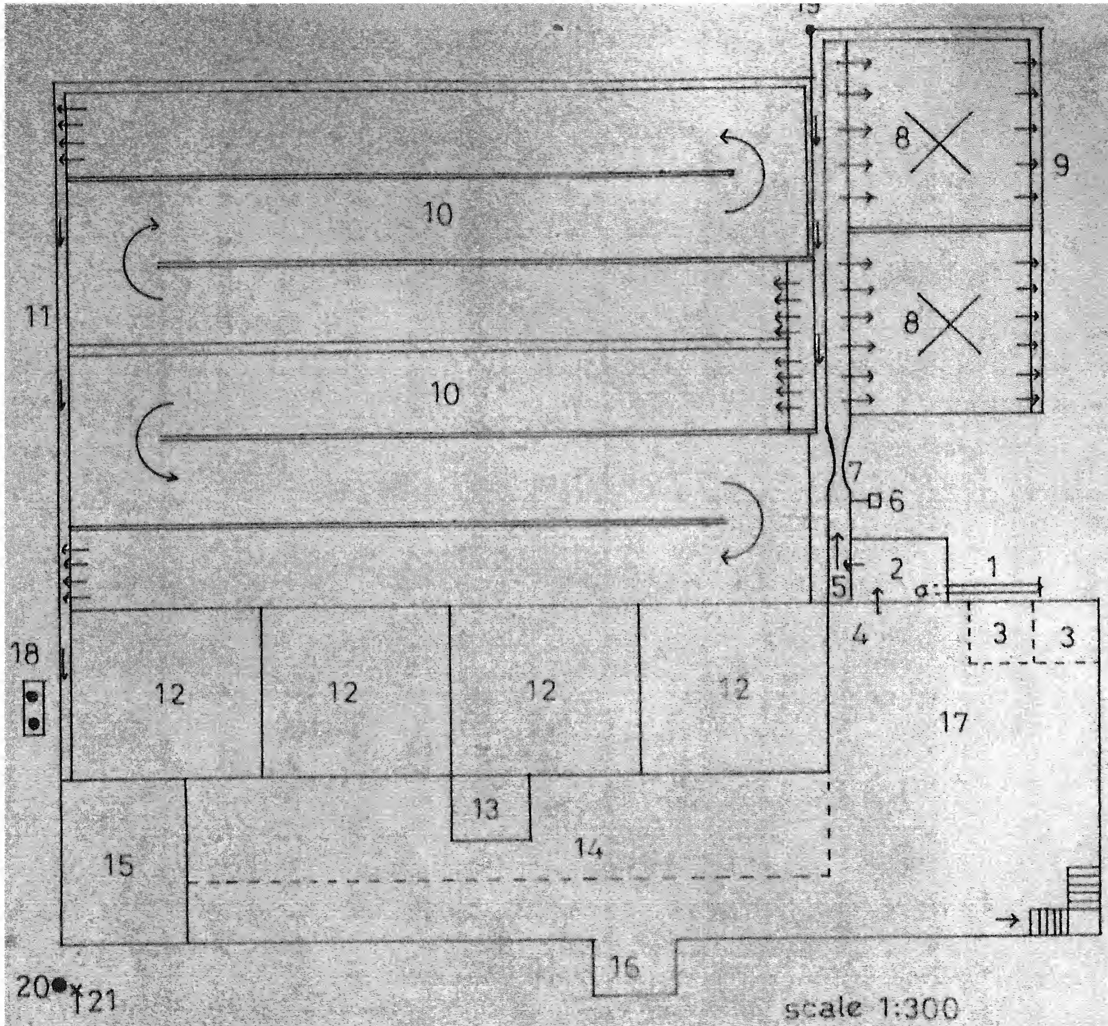
Treatment units at the Laxminarayana Giri Water Treatment Plant consist of pre-chlorination, rapid mixing of coagulant by hydraulic jump, flocculation, sedimentation, rapid sand filtration, and post-chlorination. Details of these units are given in Table 6.1 while Fig. 6.1 gives the layout of treatment units along with the location of the pilot filters employed in the present study.

6.2 Water quality

A detailed investigation on the raw as well as the treated water quality in the Bhopal area was undertaken about a decade ago by the National Environmental Engineering Research Institute Field Center, Bhopal (Sastry, Aboo and

Table 6.1 - Details of the treatment units at the Laxminarayana Giri Water Treatment Plant, Bhopal

Unit (1)	Number (2)	Details (3)	
Alum preparation tank	2	Capacity:	65,700 l
Flocculator	2	Size:	7.6 m x 7.6 m x 4.41 m
		Alum dose:	11 - 18 mg/l
		Time of agitation:	60 min
Settling tank	2	Type:	rectangular
		Size:	30.5 m x 10.63 m x (4.56 + 3.5)/2 m
		Detention time:	4 to 5 hr
		Overflow rate:	30-35 cu m/sq m/day
Filter bed	4	Size:	7.9 m x 7.1 m x 3.25 m
		Media size:	e.s. 0.47 mm u.c. 1.6
		Filtration rate:	4.86 m/h
Wash water tank	1	Size:	14.85 m x 8.97 m x 1.93 m
Clear water reservoir	2	Capacity:	6 mld



LEGEND

01 raw water rising main
02 raw water tank
03 alum solution tanks
04 point of alum feed
05 raw water channel
06 flow indicator
07 hydraulic jump
08 flocculators
09 flocculated water channel
10 settling tanks
11 settled water channel
12 filter beds
13 air compressor
14 filter gallery
15 chlorination room
16 toilet
17 pump house
18 pilot filters
19 prechlorination cylinder
20 existing man-hole
21 raw water tap

Figure 6.1 - Layout of the Laxminarayana Giri Water Treatment Plant, Bhopal

Khare, 1970). Raw water turbidity and coliform bacteria (MPN/100 ml) data for a period of two years (November 1, 1978 – October 31, 1980) were collected from the plant records and a frequency diagram for turbidity and coliform count (Fig. 6.2) indicates that the raw water is low in turbidity and more than sixtyfive percent of the time turbidity is less than 20 ppm (APHA). Higher values are observed in the period October-December. Mean and standard deviation of the turbidity values are 18.5 ppm and 4.98, respectively. The chemical characteristics of the raw water as per the procedure described in the <u>Standard Methods</u> (1975), is given in Table 6.2.

Table 6.2 - Chemical characteristics of raw water

Constituents (1)	Concentration, mg/l (except pH) (2)
pH	7.3-8.3
Total dissolved solids	230-480
Total hardness	60-80 (as $CaCO_3$)
Calcium hardness	37-50 (as $CaCO_3$)
Alkalinity	100-120 (as $CaCO_3$)
Chlorides	15-25

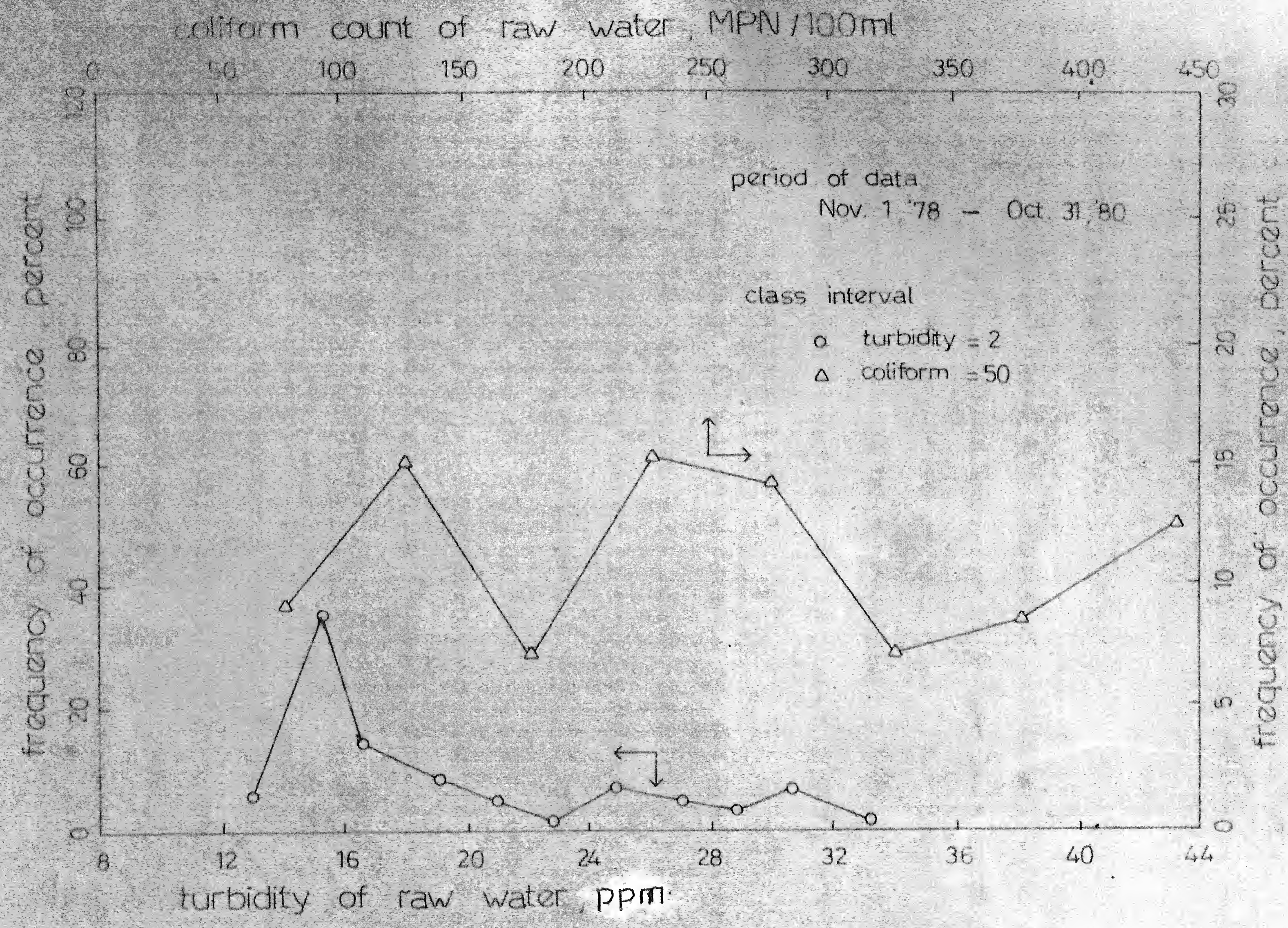


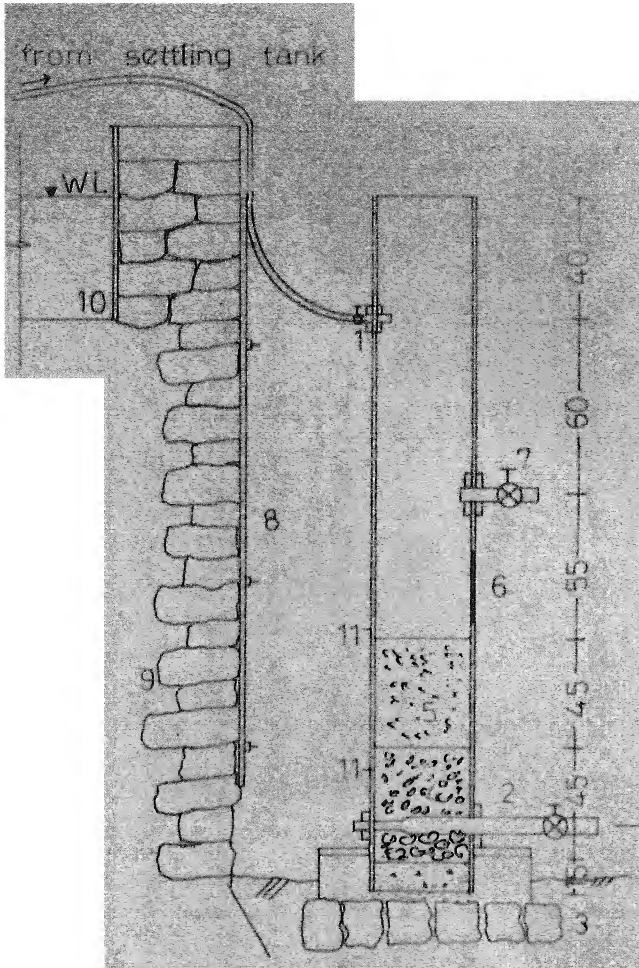
Figure 6.2 – Frequency diagram of raw water quality

Bacteriological quality of the raw water is more uniform and the coliform count (MPN/100 ml) vary from 150-300. Problem resulting from algae present in the raw water has been common during summer.

6.3 Pilot filters

Figure 6.3 shows the details of a pilot filter. The number of pilot filter required at a time on a particular site depends on the objective of the pilot plant experiments. This, in turn, is governed by constraints of funds, time and manpower. The major objective of the proposed study was an engineering demonstration of the applicability of the proposed stone-dust filter in reference to the traditional sand filter while confirming some of the significant observations of the laboratory filtration experiments. Hence, two pilot filters, one with stone-dust and the other with sand, were employed for conducting parallel experiments. However, the actual plant performance data spanning the duration of the pilot plant study (August, 1980 - June, 1981) were also available for comparison.

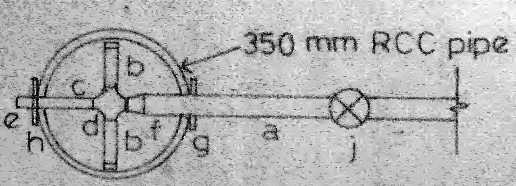
The pilot filters were made of 350 mm ID RCC pipe and this satisfied the minimum recommended diameter of 150 mm needed for direct application of pilot plant data to full scale unit (metcalf and Eddy, Inc., 1979). The pilot filters were located on a masonry platform near the settled water channel (Fig. 6.1) where it was convenient to



section through filter
scale 1:30

01 filter inlet ,25 mm ID
02 filter outlet ,40 mm ID
03 masonry platform
04 supporting media
05 filter media
06 inspection window
07 backwash waste outlet
08 manometer board
09 existing masonry wall
10 settled water channel
11 ports for headloss measurement

all dimensions are in cm



mark	description		material	no. reqd
a	40mm ID	30 cm	g.i.	1
b	25 mm ID	10 cm	g.i.	2
c	25 mm ID	15 cm	g.i.	1
d	25 mm ID	cross	g.i.	1
e	25 mm ID	plug	g.i.	3
f	40/25 ID	nipple	g.i.	1
g	40 mm ID	check nut	g.i.	1
h	25 mm ID	check nut	g.i.	1
j	40 mm ID	s.v.	g.m.	1

underdrainage system
scale 1:20

Figure 6.3 – Details of pilot filter

to obtain coagulated-settled water required for filtration experiments as well as raw water required for the direct filtration studies. Also, the pilot filters could be conveniently backwashed using the existing backwashing facilities and the filtered water as well as backwash waste could be conveniently disposal of.

Each pilot filter unit was equipped with inlet, outlet, backwash waste valve and arrangements for headloss measurement. No provision was made for collection of samples at different depths. The underdrainage system consisted of a distributor arm in the form of a cross, each arm being provided with four-6 mm holes at an angle of 30 degrees from the vertical axis. The total area provided was 0.49 percent of the filter bed area. An orifice plate was provided in the delivery pipe to avoid excessive flow at the beginning of a filter run. A transparent perspex strip was incorporated along the depth of the filter column and was provided with markings showing the top of the media surface and various percent bed expansion to which the filter bed could be backwashed. The filter bed for both the stone-dust and sand pilot filters consisted of 45 cm depth of media (d_m 0.84 mm, e.s. 0.63 mm, u.c. 1.55). Use of a 45 cm filter bed depth instead of a conventional 75 cm bed depth was primarily dictated by the limitation of the pilot filters in terms of available operational head above the media. It is to be noted, however, that such a depth would nevertheless allow

the filter to be operated on a headloss limit criterion with sufficient unutilized depth minimizing the risk of turbidity breakthrough. This is in line with the observations of Adin, and Rebhun (1977) and is also also predicted by the data on operational optima (Table 5.4). It is important to note that in a conventional 75 cm deep filter about half of the filter bed depth remains unutilized at the end of a run when the filter is backwashed on the basis of headloss criterion and this minimizes the risk of turbidity breakthrough. A coarser filter media (e.s. 0.63 mm, u.c. 1.55), compared to the size (e.s. 0.47 mm, u.c. 1.6) in use in the actual filter unit, was provided for deep penetration of the particulate matter and consequently obtaining longer filter runs (Committee Report, 1972). Use of a coarser media would also facilitate the direct filtration studies. Results of Adin, and Rebhun (1977), and data of operational optimum (Table 5.4) also support the necessity of a coarser media in the filtration work.

Since the water level of the settled water channel was almost the same as that required in the filters, the settled water was syphoned directly from the settling tank. This arrangement ensured continuous supply of the coagulated-settled water even during periods of sudden power failures. Separate connections were provided to each filter but both the filters were interconnected so as to maintain the same water level in both filters. The filtration rate was

monitored by allowing the filtered water to flow through a V notch and a constant filtration rate (when required) was obtained by manual control of the delivery valve. Backwashing was done using the existing backwashing facilities. A 20 mm ID ferrule using a sluice valve was provided on the existing pipe line. The desired flow of backwash waste was adjusted with the sluice valve and the flow was monitored through a V notch. No auxiliary air scour was provided during backwashing. Backwashing was done with a wash water rate of 50-60 and 40-50 m/h for the stone-dust and sand filters, respectively so as to achieve comparable bed expansion.

6.4 Operation of pilot filters

Both the pilot filters were operated in parallel for a period of eleven months (August, 1980-June 1981) spanning over various seasonal conditions. Even though the longer filter runs were possible for the stone-dust filter, for the sake of convenience the filter run was terminated between 27-32 hr or earlier if the headloss limit criterion of 1.7-1.8 m was reached. The sand filter reached the later criterion first; however, the stone-dust filter, in such a case, was operated for a 20-25 percent longer duration in comparison to the sand. During a filter run, readings for the headloss and effluent turbidity (measured in ppm (APHA) in a turbiditimeter manufactured by the Aplab Electronics Private Limited, Bombay) were taken at various time intervals.

Also, the bacteriological quality (presumptive coliform MPN/100 ml) of the filtered water was monitored. A relation between the turbidity in NTU and ppm (APHA) was prepared (Fig. 6.4) using a standard turbidity suspension as described in the Standard Methods (1975). This allowed for a comparison of the pilot plant data with that of the laboratory filtration experiments. The performance of the stone-dust and the sand pilot filters under three modes of operation, i.e., constant rate, declining rate and direct filtration was compared in terms of effluent quality and length of the filter run. Additionally the plant performance data (constant rate filtration) was also available for comparison. The quantity of backwash water needed for both the filters was also recorded as percent of the product water. All the modes of operation could not be performed simultaneously, but in a particular season parallel filter runs using both the media were carried out under all the three modes.

For constant rate filtration, runs were limited to the two filtration rates, viz., 5 and 7 m/h. For declining rate filtration, the delivery valve was adjusted for a particular filtration rate (7.5 m/h) at the beginning of the filter run and was kept undisturbed during the entire run. Additional observations of the filtration rate were taken at various intervals of time. For the direct filtration studies, raw water (uncoagulated) was led to the filter from the raw water tap (point 21 in Fig. 6.1) using a 50 m

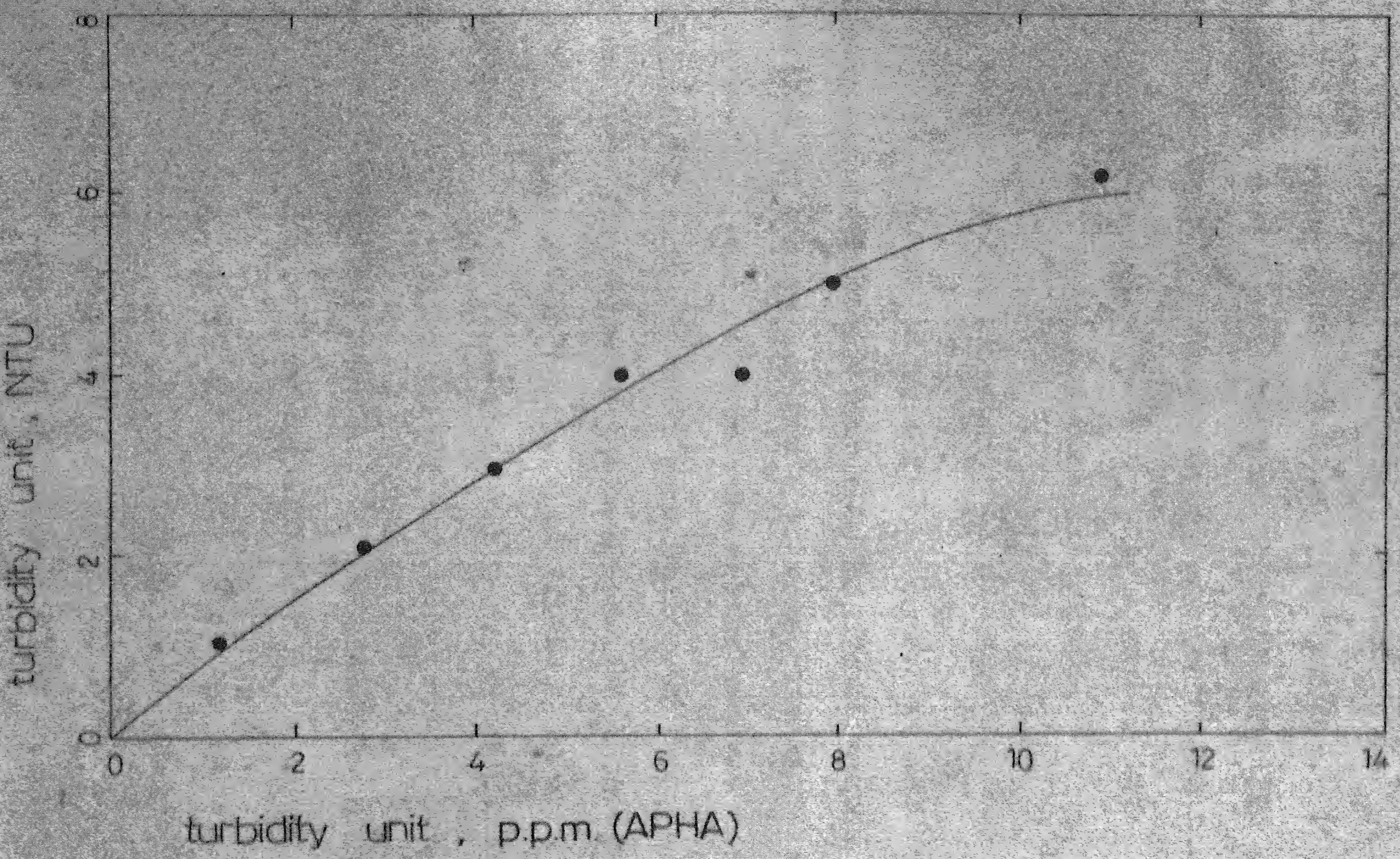


Figure 6.4 - Relation between turbidity units

long flexible hose pipe and alum was dosed from a stock solution bottle allowing about 1.5 min mixing before the dosed water entered the filter. Regarding the alum dose, several dosages in the vicinity (usually about 20-40 percent on the lower side) of the dose being employed in the actual plant for coagulation preceeding constant rate filtration were employed. This allowed for a limited study of the effect of alum dose on direct filtration.

6.5 Results and discussion

Performance data for the stone-dust and sand pilot filters, operated for a duration of eleven months are presented in Tables 6.3 and 6.4, respectively. In the case of stone-dust pilot filter, the filter run was terminated (after a duration of 20-25 percent longer than in the case of the sand filter) when the headloss limit governed the length of filter run in the sand filter. In such a case, the word greater than is used in Table 6.3 to indicate the possibility of longer filter runs and greater output of the filtered water.

6.5.1 Constant rate filtration

A closer look at the data for the stone-dust and the sand filters under constant rate filtration indicates that with the stone-dust media, it was possible to get longer filter runs with effluent quality comparable to that obtained with the sand filter. The turbidity values at the

Table 6.3 - Performance data for the stone-dust pilot filter

Period of observation	Mode of operation	No. of filter run	Filtration rate	Raw water turbidity	Effluent turbidity	Length of filter run	Quantity of product water (>)	Quantity of product water per m headloss	Coliform count of filtered water	Backwash water
			m/h	ppm	ppm (NTU)	(>) hr	cu m/sq m	cu m/sq m	MPN/100 ml	(<) %
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Aug. 15, 1980 - Nov. 14, 1980	Constant rate	3	5.0	16.28	1.0-3.0 (0.8-2.2)	26-32	119-159	158-200	2-5	2.9-3.9
		4	7.0	20-47	0.8-3.5 (0.7-2.5)	19-26	123-180	123-180	2-10	2.6-3.6
	Declining rate	4	7.5	18-38	1.2-3.9 (1.0-2.2)	30	186	255	2-3	2.5
	Direct	4	5.0	22-40	1.2-3.5 (1.0-2.5)	20	93	72	2-6	4.5
Nov. 16, 1980 - March 11, 1981	Constant rate	4	5.0	10-21	2.2-4.0 (1.6-2.8)	27-30	146-162	198-230	2-5	2.5-3.1
		4	7.0	10-22	2.5-5.0 (1.9-3.4)	29-31	157-174	160-185	5-13	2.6-2.9
	Declining rate	4	7.5	14-26	1.9-4.0 (1.5-2.8)	29	230	300	2-8	1.6-1.8
	Direct	8	5.0	10-18	2.5-5.0 (1.9-3.4)	20	93	75	5-18	4.2
May 4, 1981 - June 26, 1981	Constant rate	3	5.0	10-17	1.0-2.7 (0.8-2.0)	30	186	233	5-14	2.8
		2	7.0	12-18	1.4-2.7 (1.2-2.1)	24-26	165-180	170-190	8-22	2.6-2.8
	Declining rate	3	7.5	10-16	1.2-2.5 (1.0-1.9)	30	240	320	9-17	1.2-2.1
	Direct	3	5.0	14-21	2.0-3.5 (1.7-2.2)	20	93	75	11-27	4.8

Table 6.4 - Performance data for the sand pilot filter

Period of observation	Mode of operation	No. of filter run	Filtration rate	Raw water turbidity	Effluent turbidity	Length of filter run	Quantity of product water	Quantity of product water per m headloss	Coliform count of filtered water	Backwash water
			m/h	ppm	ppm (NTU)	hr	cu m/ sq m	cu m/sq m	MPN/ 100 ml	%
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Aug. 15, 1980 - Nov. 14, 1980	Constant rate	3	5.0	16-28	1.0-3.2 (0.8-2.3)	18-24	83-110	57-75	2-5	3.0-4.2
		4	7.0	20-47	1.1-4.0 (0.9-2.8)	12-20	90-150	50-82	2-8	2.8-4.0
	Declining rate	4	7.5	18-38	1.1-3.4 (0.9-2.4)	20-26	170-187	112-125	2-5	2.5-2.65
	Direct	4	5.0	22-40	1.2-3.9 (1.0-2.7)	10-16	48-76	28-42	2-8	5.2-8.0
Nov. 16, 1980 - March 11, 1981	Constant rate	4	5.0	10-21	2.0-4.0 (1.5-2.8)	20-28	107-150	71-100	2-8	2.0-4.0
		4	7.0	10-22	1.8-4.5 (1.4-3.1)	20-29	150-218	90-128	9-15	2.4-2.8
	Declining rate	4	7.5	14-28	1.8-4.0 (1.4-2.8)	26-28	209-240	135-145	2-11	1.75-1.90
	Direct	8	5.0	10-18	2.5-5.0 (1.9-3.4)	12-18	57-85	33-50	5-18	4.8-7.0
May 4, 1981 - June 26, 1981	Constant rate	3	5.0	10-17	1.0-2.5 (0.8-1.9)	28-30	150-165	100-110	3-11	2.0-2.4
		2	7.0	12-18	1.5-3.0 (1.2-2.2)	18-21	140-165	86-100	8-33	3.0-3.5
	Declining rate	3	7.5	10-16	1.1-2.8 (0.9-2.1)	26-28	200-300	120-135	3-14	1.8-2.2
	Direct	3	5.0	14-21	2.0-3.0 (1.5-2.2)	11-14	52-58	30-35	11-23	6.0-7.5

end of the filter run in both the pilot filters were slightly greater than 2 NTU. Bacteriological effluent quality of the pilot filters, at 5m/h when compared to that of the full-scale plant, was poor (MPN 2 or less than 2 per 100 ml in 80 percent observations) but comparable in view of use of coarser media in pilot filters. In spite of higher backwash water rate requirement, the stone-dust filter required lesser percent of product water.

6.5.2 Declining rate filtration

Reduction in the filtration rate (as percent of initial filtration rate) during the filter run for both the pilot filters is presented in Fig. 6.5. The results show that in the case of the stone-dust, reduction in the filtration rate was lesser, indicating advantages of the stone-dust media for this type of filtration. Thus the stone-dust filter may need lesser number of units for influent flow splitting, resulting in saving of capital and maintenance cost. In fact, in the existing filters equipped with rate-of-flow controllers and utilizing the stone-dust media output would be affected to a lesser extent, when the rate-of-flow controllers go out of order. Both the stone-dust and sand filters produced longer filter runs with better effluent quality and greater output of the filtered water under declining rate filtration compared to the constant rate filtration.

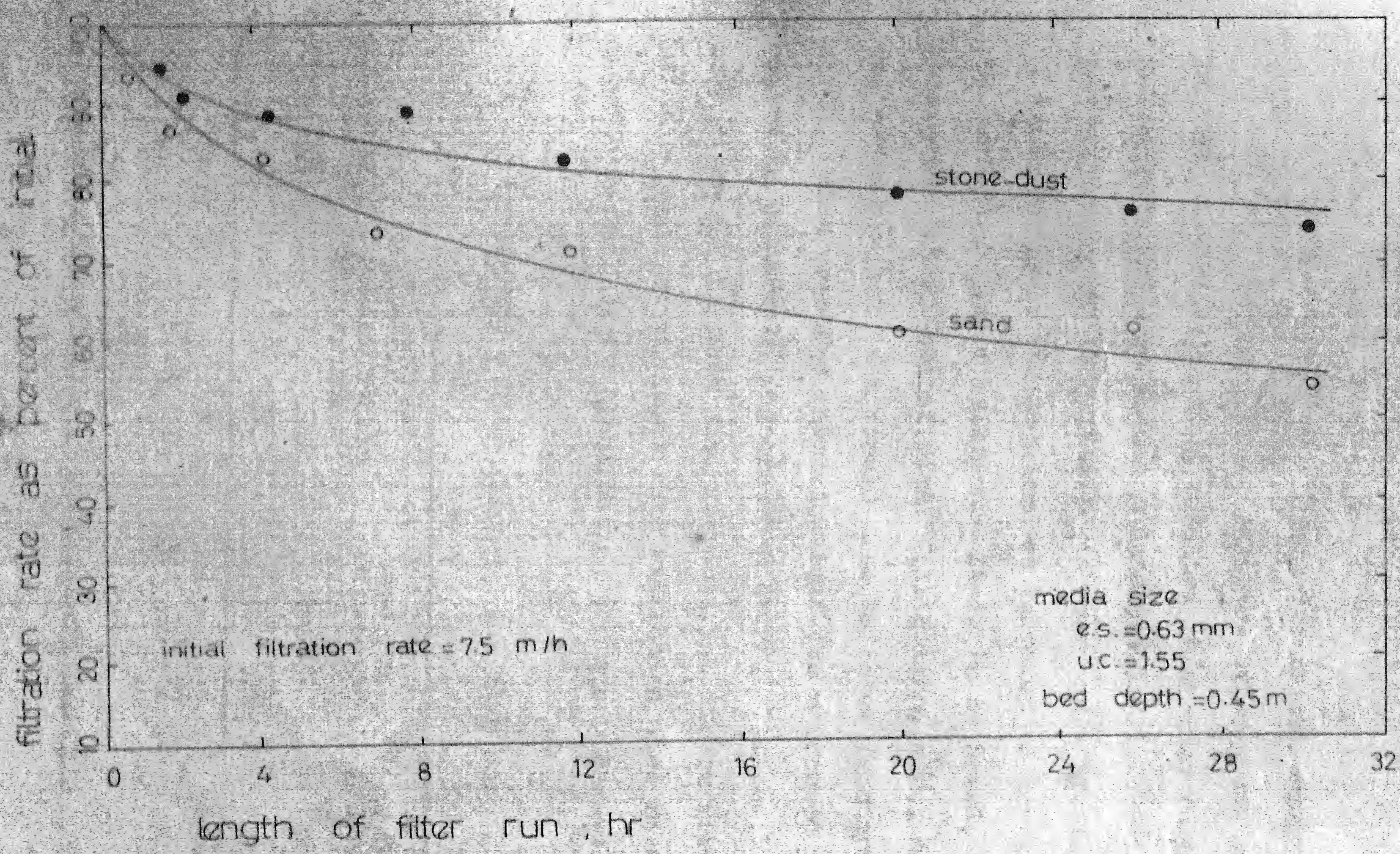


Figure 6.5 - Filtration rate during filter run in declining rate filters

6.5.3 Direct filtration

Results of the direct filtration study (Tables 6.3 and 6.4) reveal that for both the stone-dust and sand filters, direct filtration resulted in shorter duration of filter runs for same value of headloss limit. Effluent quality from both the filters was poor and a greater percent of backwash water was required as compared to constant rate and declining rate filtration. It is to be noted, however, that other advantages of direct filtration, viz., by passing the sedimentation tank should also be taken into consideration. More detailed investigations are warranted in this regard to provide an integrated picture. Table 6.5 gives a comparison of the alum dose required for direct filtration and alum dose for constant rate filtration used in the pilot as well as full-scale plant during the study period.

Table 6.5 - Comparison of the alum dose

Raw water turbidity ppm (APHA)	Dose for constant rate filtration mg/l	Dose for direct filtration mg/l	Saving of chemical percent
(1)	(2)	(3)	(4)
10-21	11.4	9.0	22
21-40	17.0	11.5	32

Thus, it is possible to have 22-32 percent alum with direct filtration.

6.5.4 Headloss build up in a filter

Figures 6.6 and 6.7 show the headloss build up during a filter run for the stone-dust and sand pilot filters, for various modes of operation. A glance at the figures indicates that similar pattern of behaviour was obtained in both the filters except that in the case of the stone-dust values of headloss was lower than the corresponding values of headloss in the sand filter. On comparison of values (Fig. 6.6 and 6.7), it is felt that it would be possible to adopt higher filtration rate (10 m/h or even greater) in the case of the stone-dust filter at the same time obtaining satisfactory performance.

6.5.5 Stone-dust - as a high rate filter

Comparatively lower values of headloss in the case of the stone-dust filter (Fig. 6.6) indicate the probability of using higher filtration rates. Due to limitation of available head and existing facilities, only limited observations (2 filter runs) at 10 m/h filtration rate could be taken in the summer period. Results indicated that the effluent turbidity was more than 2 NTU for most of the period and also the presumptive coliform MPN greater than 15/100 ml for both the filters. For the stone-dust media filter runs were of 22-24 hr duration as compared to

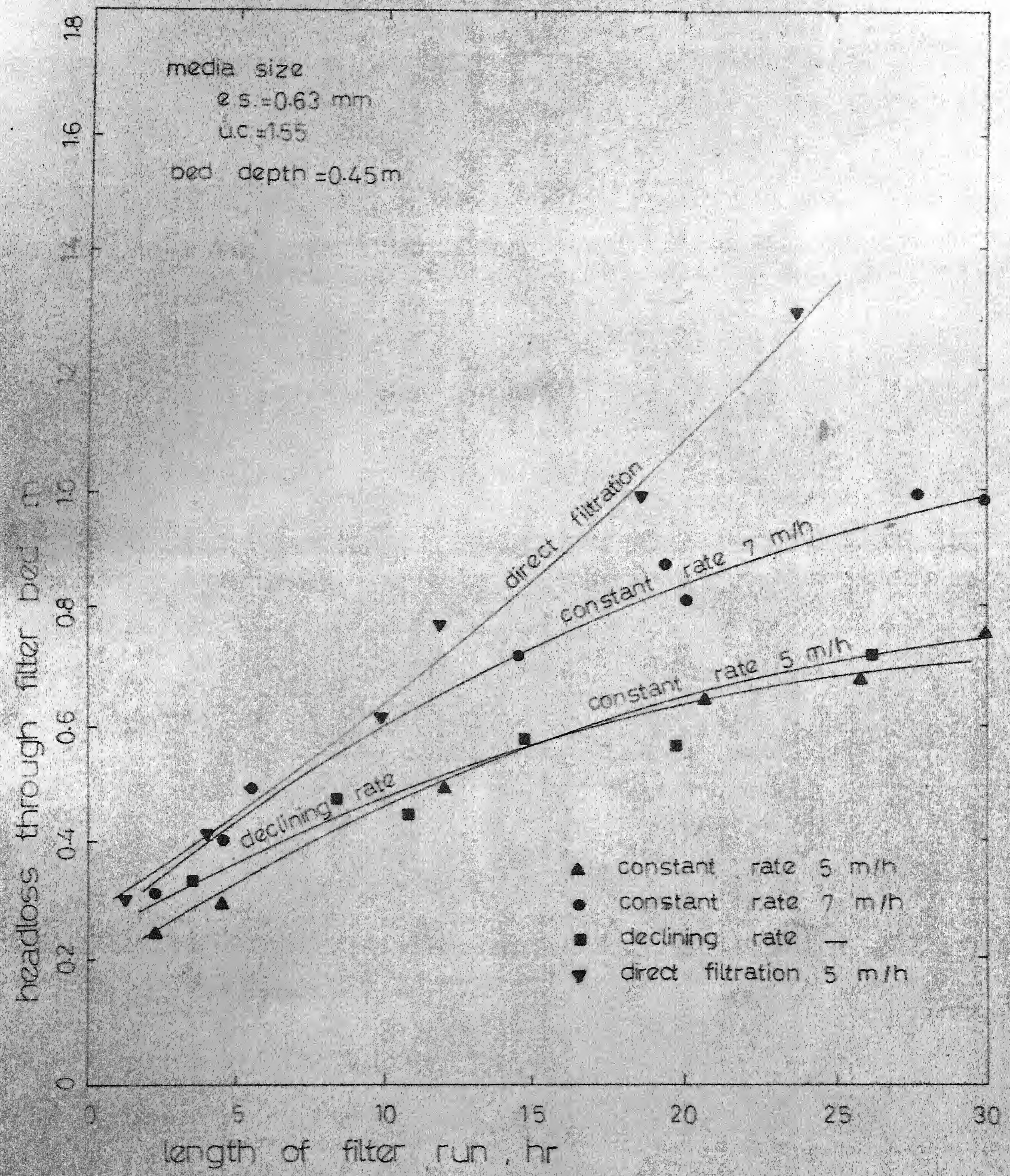


Figure 6.6 - Headloss buildup in a filter bed in stone-dust pilot filter

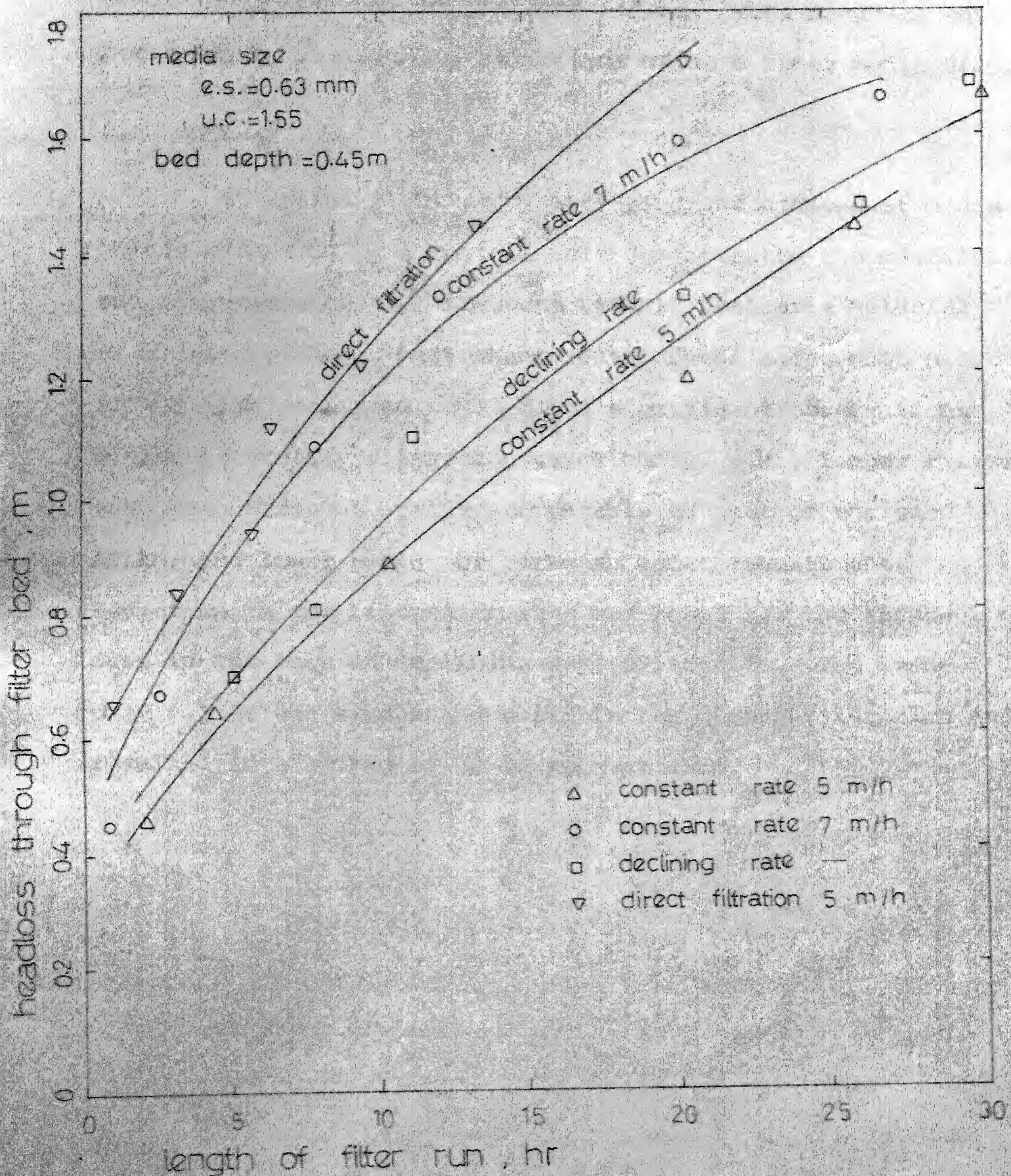


Figure 6.7 – Headloss buildup in a filter bed in sand pilot filter

10-12 hr in the case of the sand filter. This suggests the necessity of further investigations using a finer media size.

6.6 Summary

The pilot plant study employing the stone-dust media (along with sand as a control unit) demonstrated the usefulness and advantages of this low cost readily available material as a filter media. Performance data of the stone-dust pilot filter also confirmed some of the significant observations of the laboratory filtration experiments, e.g., longer filter runs with effluent quality comparable to that of the sand filter and lower amount of backwash water requirement. Reduction in the filtration rate was lower for the stone-dust in the case of declining rate filtration. The stone-dust filter was also found suitable for direct filtration and resulted in a saving of 22-32 percent alum.

7. SUMMARY AND CONCLUSIONS

The results of the present study indicated the potential usefulness of the basaltic stone-dust as a filter media in water treatment. In spite of some of the limitations, the stone-dust media has some advantages from operational viewpoint. Considering its low cost and ready availability, it should find application at places where sand has to be transported from a long distance. Specific conclusions that may be drawn from the data on media characterization, laboratory filtration experiments and the pilot plant study are summarized below.

(1) Basaltic stone-dust as obtained from the site has a lower percent of usable material as compared to sand when processed for use as a filter media.

(2) The stone-dust media has a specific gravity value comparable to that of sand, but has a greater amount of bed porosity which results in lower initial headloss value, however, a higher backwash water rate is required for obtaining comparable bed expansion in backwashing.

(3) The stone-dust media has lower sphericity which presumably results in a higher degree of attrition/abrasion when subjected to 100 hr backwash.

(4) Lower value of the filterability number for all the combinations of media size, bed depth and filtration rate indicates filtration suitability of the stone-dust

media for alum coagulated suspension. Also the stone-dust filter has a lesser dependence on the filtration rate.

(5) Laboratory filtration experiments indicate that, with the stone-dust media, it is possible to obtain longer filter runs at the same time obtaining effluent turbidity value comparable to that in a sand filter.

(6) Operational optimum (depth of filter bed and length of filter run) for the stone-dust and sand media when both the headloss and turbidity ratio limit reach at the same time, indicates that about fifty percent of the normal bed depth provided in the conventional filter (75 cm) is utilized. Both the stone-dust and sand media of a coarser specification indicate economical performance in terms of output of the filtered water.

(7) The stone-dust media has a higher value of clean bed filter coefficient compared to sand. The stone-dust filter is less sensitive to fluctuations in the influent turbidity and the filtration rate, but its performance is more dependent on the media size.

(8) For all combinations of media size, filtration rate and influent concentration, the stone-dust filter has a greater storage capacity of particulate matter compared to sand.

(9) On a pilot plant scale, operation with different modes of filtration at the site of Laxminarayana Giri Water Treatment Plant, Bhopal, the performance of the stone-dust

filter was observed to be comparable to the sand filter with additional advantages of longer filter run and lesser amount of backwash water requirement. The stone-dust media is suitable for use in direct filtration. In declining rate filtration, reduction in filtration rate during a filter run in the stone-dust filter is lower than the corresponding value in the sand filter.

8. PRACTICAL SIGNIFICANCE

The research outlined in this thesis was centered around a practical engineering problem which involved evaluation and utilization of a locally available waste material (basaltic stone-dust) as a filter media in water filtration. This problem stemmed from the situation prevailing in the State of Madhya Pradesh, India, where sand of required quality for use as a filter media generally needs to be transported through a long distance. Apparent specific advantages were its low cost and elimination of the operation required (crushing) for getting appropriate size for use as a filter media.

Inspite of some of the limitations, the stone-dust media showed some apparent advantages which could be beneficially employed in water treatment. With longer filter runs frequency of backwashing is reduced and this reduces the need for skilled operation all the times. The stone-dust filter is less sensitive to fluctuations in influent quality and quantity to which a normal water treatment plant is usually subjected.

The Public Health Engineering Department, Government of Madhya Pradesh, Bhopal showed interest in this work and provided the necessary funds and facilities for conducting the pilot plant studies. The basic idea of this plant study

is not only to demonstrate the applicability of this low cost material in a real-world situation but also focuss the attention of the concerned authorities so that this media may find a place as a substitute of sand in water treatment.

9. SUGGESTIONS FOR FURTHER WORK

In view of the findings of the present study, it is telt that further work can be pursued on the following aspects.

(1) Conversion of a full scale filter unit to a stone-dust filter and close monitoring of its performance.

(2) Pilot plant studies at the site of a treatment plant where raw water quality variations are significant.

(3) Suitability of the stone-dust media as a high rate filter using a finer media size, and

(4) More detailed studies on direct filtration taking into consideration engineering as well as economic advantages that may emerge.

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APPENDIX TABLES

Table A1 - Headloss and turbidity ($\frac{c}{c_o}$) data for filterability number determination - stone-dust

Set no.	Media size	Filtration rate (V_o) m/h	Influent turbidity (c_o) NTU	c/c_o at indicated depths 11 cm	19 cm	29 cm	41 cm	68 cm	Headloss at indicated depths, cm 11 cm	19 cm	29 cm	41 cm	68 cm
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1		5.0	10.38	0.25	0.17	0.12	0.08	0.08	4.9	7.2	9.7	13.5	20.2
2	d_m 0.46 mm	7.5	10.40	0.25	0.21	0.18	0.16	0.10	6.6	9.7	11.4	16.5	23.0
3		10.0	10.00	0.17	0.12	0.10	0.09	0.04	10.3	15.2	20.5	27.1	39.8
4	e.s. 0.44 mm	5.0	24.33	0.11	0.08	0.08	0.06	0.06	3.6	4.9	6.3	7.9	12.6
5	u.c. 1.09	7.5	25.50	0.08	0.05	0.04	0.03	0.03	6.9	9.0	11.4	15.4	21.7
6		10.0	23.67	0.13	0.11	0.08	0.06	0.04	12.2	15.0	19.1	27.5	35.8
7		5.0	9.88	0.21	0.14	0.13	0.11	0.06	3.4	4.8	6.6	8.1	13.3
8		7.5	10.33	0.16	0.13	0.08	0.07	0.04	4.8	6.5	8.9	11.8	17.9
9	d_m 0.54 mm	10.0	10.50	0.19	0.13	0.10	0.07	0.05	8.6	12.2	20.3	30.5	35.7
10	e.s. 0.53 mm	5.0	24.33	0.14	0.08	0.06	0.06	0.04	4.2	5.8	7.8	10.3	15.7
11	u.c. 1.09	7.5	24.83	0.16	0.08	0.06	0.04	0.03	6.4	9.1	12.6	16.9	26.2
12		10.0	24.67	0.25	0.13	0.08	0.04	0.03	8.2	12.6	17.6	23.4	35.4
13		5.0	11.00	0.30	0.23	0.15	0.09	0.06	3.6	5.2	7.0	9.1	13.5
14		7.5	10.42	0.21	0.15	0.11	0.09	0.05	5.3	7.6	10.2	13.3	18.4
15	d_m 0.65 mm	10.0	10.83	0.22	0.17	0.11	0.08	0.06	6.6	9.7	13.5	17.9	26.9
16	e.s. 0.62 mm	5.0	25.33	0.16	0.10	0.05	0.03	0.03	3.9	5.4	7.5	9.3	13.7
17	u.c. 1.04	7.5	25.17	0.19	0.12	0.08	0.03	0.02	5.5	9.1	12.1	15.6	22.4
18		10.0	23.83	0.23	0.16	0.10	0.06	0.04	6.8	9.8	13.1	17.4	25.3

Table A2 - Headloss and turbidity ($\frac{c}{c_o}$) data for filterability number determination - sand

Set no.	Media size	Filtration rate(V_o) m/h	Influent turbidity(c_o) NTU	c/c_o at indicated depths					Headloss at indicated depths, cm				
				11 cm	19 cm	29 cm	41 cm	68 cm	11 cm	19 cm	29 cm	41 cm	68 cm
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1		5.0	10.38	0.25	0.20	0.16	0.14	0.10	6.2	10.2	14.9	20.2	29.1
2		7.5	10.40	0.30	0.23	0.19	0.15	0.11	7.9	12.6	18.2	24.0	42.3
3	d_m 0.46 mm	10.0	10.00	0.18	0.13	0.08	0.07	0.05	14.9	23.3	33.3	44.4	64.9
	e.s. 0.44 mm												
4	u.c. 1.09	5.0	24.33	0.14	0.11	0.08	0.07	0.05	6.8	10.3	14.2	17.3	26.0
5		7.5	25.50	0.11	0.07	0.06	0.04	0.03	11.2	14.9	19.9	26.4	37.5
6		10.0	23.67	0.22	0.10	0.11	0.07	0.05	15.6	23.0	33.0	44.1	64.1
7		5.0	9.88	0.18	0.14	0.13	0.10	0.06	4.7	5.1	10.4	14.1	20.9
8		7.5	10.33	0.22	0.12	0.10	0.07	0.04	7.2	15.4	16.7	22.4	32.4
9	d_m 0.54 mm	10.0	10.50	0.27	0.17	0.13	0.08	0.05	16.5	23.1	31.1	41.6	59.7
	e.s. 0.53 mm												
10	u.c. 1.09	5.0	24.33	0.21	0.14	0.08	0.04	0.04	5.9	9.2	12.5	17.3	25.7
11		7.5	24.83	0.20	0.14	0.10	0.04	0.03	9.5	15.8	21.8	33.4	40.6
12		10.0	24.67	0.37	0.19	0.09	0.04	0.03	12.7	19.0	25.9	34.9	51.4
13		5.0	11.00	0.32	0.20	0.15	0.11	0.06	5.0	7.2	9.7	13.2	18.5
14		7.5	10.42	0.17	0.14	0.11	0.07	0.06	6.6	9.7	13.3	17.7	24.3
15	d_m 0.65 mm	10.0	10.83	0.30	0.21	0.14	0.09	0.06	9.1	14.0	18.4	27.0	39.3
	e.s. 0.62 mm												
16	u.c. 1.04	5.0	25.33	0.15	0.10	0.06	0.04	0.03	7.5	10.3	14.2	17.3	25.9
17		7.5	25.17	0.16	0.11	0.06	0.04	0.02	11.2	14.9	19.5	26.4	37.5
18		10.0	23.83	0.28	0.17	0.11	0.06	0.05	15.0	23.0	32.9	43.6	64.0

Table B1 - Turbidity and headloss data for stone-dust laboratory filter (Media size: d_m, 0.46 mm; e.s., 0.44 mm; u.c., 1.09)

Filter run	Filtration rate m/h	Time hr	Influent turbidity (c_o) NTU	Turbidity at indicated depth, (c), NTU					Headloss at indicated depths, cm				
				11 cm	19 cm	29 cm	41 cm	68 cm	11 cm	19 cm	29 cm	41 cm	68 cm
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1a	5.0	0.50	10.00	1.60	1.10	1.40	0.85	0.55	4.0	6.2	9.0	14.4	20.8
		2.00	10.00	1.20	0.85	1.15	0.90	0.60	8.3	10.8	13.7	20.3	27.5
		3.50	10.50	1.60	1.10	0.80	1.00	0.50	14.9	17.6	20.5	25.1	31.0
		5.50	10.00	2.30	1.30	0.85	0.70	0.65	25.9	29.4	32.4	38.3	46.3
		7.00	9.50	1.80	1.10	1.20	1.20	0.70	33.1	37.0	40.5	45.6	53.4
		9.50	9.80	4.75	1.05	0.80	0.80	0.60	56.2	60.5	64.0	69.3	77.6
		12.00	10.00	7.35	1.10	1.00	0.60	0.70	82.2	87.7	91.7	96.2	107.7
1b	5.0	0.50	11.50	2.70	2.20	2.30	2.20	0.70	5.5	7.8	10.6	13.9	19.4
		2.00	10.20	4.70	1.70	1.30	2.60	0.75	10.4	13.2	15.8	18.9	23.7
		3.50	9.00	1.40	1.20	1.80	1.20	0.60	12.5	14.8	17.3	20.2	23.9
		5.50	10.00	2.20	0.90	0.85	4.20	0.60	24.0	27.0	30.1	33.4	39.1
		7.00	11.00	3.10	1.20	1.10	0.75	0.90	39.3	43.1	45.3	48.9	54.2
		9.50	9.50	2.20	1.85	1.05	1.30	0.80	53.3	66.2	70.2	73.3	77.2
		12.00	10.00	7.00	1.10	1.00	0.70	0.75	89.7	93.0	96.2	99.7	105.7
1c	5.0	0.50	12.00	3.00	2.90	2.10	-	0.60	5.4	7.7	10.5	13.7	17.5
		2.00	10.50	0.85	0.80	0.80	0.60	0.40	8.8	11.3	13.9	16.8	23.8
		3.50	9.50	1.30	0.90	0.70	0.60	0.30	16.3	19.6	22.9	26.4	33.0
		5.50	11.50	3.50	0.70	0.50	0.50	0.40	32.3	35.3	39.2	42.7	40.2
		7.00	10.00	1.80	1.20	0.70	0.65	0.35	45.3	49.0	52.1	55.1	60.4
		9.50	11.50	5.60	2.30	1.40	0.80	0.60	85.5	89.6	92.8	96.5	102.2
		12.00	10.00	5.20	0.90	0.80	0.55	0.40	101.6	106.3	109.5	113.1	121.0

Contd...

Table B1 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
2a	5.0	0.50	26.50	3.40	1.10	1.10	0.75	0.55	6.4	8.7	11.5	15.0	22.6
		2.00	24.00	4.20	1.25	1.30	0.90	0.70	17.5	19.5	22.0	24.8	29.2
		3.50	26.00	5.80	1.90	1.80	1.05	0.65	35.3	37.7	40.3	43.2	48.7
		5.50	25.50	17.00	5.10	4.20	1.50	0.90	76.4	79.8	62.6	86.5	92.5
		6.75	25.00	20.00	6.60	8.50	4.10	3.75	104.8	109.2	112.4	115.7	122.1
2b	5.0	0.50	24.50	8.40	10.50	2.50	1.90	1.90	6.0	10.2	14.4	19.4	26.0
		2.00	23.00	2.40	1.80	1.40	1.60	1.60	15.2	17.6	21.0	24.2	30.0
		3.50	25.50	5.80	1.70	1.90	1.15	0.90	30.3	33.0	35.9	39.4	43.6
		5.50	23.00	5.70	2.80	0.75	1.10	0.75	54.2	56.1	59.0	61.9	66.0
		6.75	23.00	11.00	2.80	1.60	1.30	0.85	78.5	82.0	85.0	89.0	92.4
2c	5.0	0.50	22.00	4.10	3.70	3.50	2.50	2.50	4.4	5.8	7.6	9.9	13.8
		2.00	25.50	4.50	5.40	3.50	2.30	1.50	13.2	15.8	18.6	21.7	27.6
		3.50	26.50	3.45	2.95	2.50	2.00	1.50	33.3	38.8	42.4	47.2	56.6
		5.50	25.50	20.00	6.40	1.80	1.80	0.90	77.4	82.3	87.0	91.3	98.0
3a	7.5	0.50	12.00	1.60	1.00	1.10	0.90	0.50	8.0	11.7	16.0	21.3	30.8
		2.00	11.00	2.00	1.80	1.30	1.60	1.00	15.8	19.4	23.3	28.1	37.0
		3.50	10.00	3.10	2.40	1.10	1.10	0.80	25.0	29.5	34.0	39.6	49.6
		5.00	11.00	3.60	1.50	1.30	0.80	0.60	41.9	47.3	52.1	57.6	68.4
		6.50	9.50	4.50	1.50	0.95	1.10	0.50	57.4	63.0	67.9	73.2	82.9
		8.00	10.00	11.50	2.60	1.20	1.30	0.50	67.2	84.4	89.4	95.1	105.4
		9.50	10.00	12.00	3.60	1.15	0.90	0.75	91.6	99.3	104.5	110.1	120.0

Contd...

Table B1 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
		0.50	10.00	1.80	1.60	1.20	0.75	0.90	7.2	10.5	14.5	19.3	30.5
		2.00	9.50	3.15	1.80	2.00	1.10	0.80	10.4	14.9	19.8	25.7	37.3
		3.50	10.00	3.60	1.40	1.10	1.25	1.00	16.5	21.4	26.3	32.3	43.6
3b	7.5	5.00	9.00	2.80	1.70	1.60	0.90	0.85	20.3	22.8	29.3	34.4	45.1
		6.50	10.00	2.40	1.50	1.20	1.00	0.70	24.8	29.5	34.5	38.5	49.3
		8.00	9.50	2.30	1.60	1.40	0.90	0.70	36.2	41.1	45.6	50.7	60.8
		9.50	9.00	10.60	3.40	1.40	1.25	0.70	48.9	54.1	58.6	64.0	75.1
		0.50	12.00	3.30	2.80	3.20	2.60	1.40	9.1	13.1	18.1	25.1	38.9
		2.00	11.00	3.50	3.10	2.90	1.20	0.75	16.1	20.4	25.0	32.6	47.2
3c	7.5	3.50	9.80	6.10	4.50	4.00	2.00	0.90	22.4	26.9	31.5	39.1	51.3
		5.00	10.50	7.80	4.50	3.60	3.00	1.20	37.0	43.0	47.2	52.3	65.3
		6.50	12.00	8.20	7.20	-	5.20	1.40	43.0	48.5	54.0	55.7	73.3
		0.50	25.00	1.40	1.30	1.20	1.10	1.10	12.3	16.6	20.8	25.8	38.0
		1.50	23.50	4.40	3.20	2.50	3.00	1.20	23.2	28.2	33.1	38.6	49.7
4a	7.5	2.50	23.00	5.20	4.20	1.70	6.00	0.75	36.4	42.3	47.4	53.0	63.7
		3.50	23.50	13.50	4.80	2.70	2.40	0.80	59.8	61.6	70.5	76.5	88.0
		5.00	25.50	18.80	7.40	5.80	3.00	1.40	93.7	103.5	109.3	115.0	125.8
		0.50	24.50	18.0	10.5	3.80	4.20	1.20	7.20	11.4	16.2	21.6	31.2
		1.50	24.00	10.20	2.70	1.20	1.20	0.60	16.4	21.7	26.8	32.7	42.9
4b	7.5	2.50	25.00	7.40	3.70	2.20	1.10	0.80	42.6	49.1	54.8	60.9	71.7
		3.50	26.00	40.00	7.80	4.40	2.80	0.80	74.6	83.5	89.3	95.4	106.2
		4.25	25.50	18.00	6.30	2.20	2.00	0.75	98.9	108.4	113.9	119.7	129.1

Contd...

Table B1 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
4c	7.5	0.50	24.00	6.00	1.80	1.50	1.20	1.20	10.2	14.0	18.4	23.9	36.4
		1.50	23.50	11.70	5.80	1.80	1.60	0.75	27.0	32.3	37.4	45.3	59.7
		2.50	24.00	11.00	11.70	5.00	2.20	0.75	45.3	50.4	56.8	60.2	72.2
		3.50	24.50	21.00	9.40	2.20	1.80	0.75	77.7	83.7	89.1	93.0	107.8
		4.25	23.80	19.00	11.50	3.00	2.40	0.80	98.7	106.9	111.9	117.3	129.2
		5.00	25.00	23.00	15.20	3.60	2.85	1.30	124.5	135.9	142.2	148.2	159.8
5a	10.0	0.50	10.50	3.50	3.90	4.40	1.60	1.10	11.9	15.1	21.3	30.9	40.9
		1.50	10.00	2.80	1.65	1.55	1.10	0.75	14.2	19.9	26.0	34.5	47.2
		2.50	9.50	2.75	3.00	2.20	1.50	0.90	18.3	24.2	30.3	38.8	51.2
		4.00	10.00	2.75	2.40	1.90	1.50	1.20	27.3	33.2	39.2	48.1	58.5
		5.50	9.80	9.20	5.20	2.80	2.20	1.20	39.0	46.5	53.2	64.3	77.0
		7.00	10.00	5.40	3.50	4.00	1.40	0.75	50.7	57.7	63.8	72.4	83.8
5b	10.0	0.50	10.00	5.20	3.10	5.10	1.70	1.00	11.0	16.1	22.1	29.0	41.8
		1.50	10.00	3.75	4.60	1.60	2.20	1.10	18.6	25.1	31.8	39.5	53.1
		2.50	11.00	6.80	1.50	-	1.70	1.30	29.5	37.0	44.1	51.5	64.5
		4.00	11.50	9.50	3.00	1.80	1.40	1.05	56.5	65.2	72.9	80.8	94.7
		5.50	12.00	12.40	5.70	3.25	2.10	1.80	75.8	85.5	92.4	99.3	111.2
		7.00	10.80	13.00	5.80	4.20	2.30	1.40	97.2	109.2	117.0	124.8	137.4
5c	10.0	0.50	11.50	20.00	11.20	10.80	4.30	1.75	10.9	16.8	23.5	30.8	46.3
		1.50	9.50	7.80	5.30	4.60	3.20	1.10	16.4	25.5	31.0	40.0	56.0
		2.50	9.50	8.20	4.50	4.00	2.20	1.10	21.2	26.5	35.0	42.9	57.7
		4.00	9.00	7.50	5.00	3.50	1.80	1.10	32.0	44.2	51.0	58.7	73.0
		5.50	10.00	10.60	2.00	2.00	1.60	1.20	53.6	62.5	67.8	77.4	92.1
		7.00	10.00	15.00	5.70	4.00	3.00	1.40	76.6	86.8	94.3	102.2	116.3

Contd...

Table B1 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
		0.50	25.50	7.00	5.00	2.40	1.90	1.40	11.5	16.3	21.7	28.8	42.8
		1.25	20.50	8.00	7.30	4.30	1.60	1.40	22.6	27.4	32.2	39.3	51.7
6a	10.0	2.00	22.00	10.00	5.50	2.20	1.40	1.10	41.5	48.3	53.7	62.0	77.1
		2.75	24.50	12.50	5.50	4.50	2.40	1.00	59.6	66.2	71.7	79.3	102.6
		3.50	23.00	18.00	5.60	4.50	1.90	1.30	87.5	35.8	101.5	109.3	120.2
		0.50	21.00	6.00	6.00	4.00	3.30	1.50	12.7	19.2	26.2	35.2	47.6
		1.25	23.00	6.70	3.70	3.10	2.40	1.30	24.5	30.8	37.2	45.2	55.8
6b	10.0	2.00	22.50	6.00	-	2.65	1.55	1.20	40.0	44.5	54.0	62.3	73.0
		2.75	25.50	7.30	4.50	3.60	1.90	1.25	56.8	64.4	70.5	78.2	88.2
		3.50	23.00	22.00	6.00	3.00	2.50	1.10	60.0	89.7	96.8	105.5	116.7
		0.50	21.50	7.00	5.80	0.90	0.85	0.70	21.0	30.7	37.8	47.2	66.3
		1.25	22.00	2.60	2.30	1.50	1.70	1.00	39.2	49.5	66.1	74.2	89.1
6c	10.0	2.00	21.50	10.00	2.80	2.50	2.20	1.60	69.7	78.8	93.8	102.0	116.3
		2.75	24.50	15.00	2.30	-	1.20	1.10	106.7	113.5	128.3	135.3	148.3
		3.50	26.00	16.00	5.20	3.30	1.60	1.30	142.0	153.0	168.2	175.0	185.9

Table B2 - Turbidity and headloss data for stone-dust laboratory filter (Media size: d_m 0.54 mm; e.s. 0.53 mm; u.c. 1.09)

Filter run	Filtration rate (V_o) m/h	Time hr	Influent turbidity (c_o) NTU	Turbidity at indicated depths (c), NTU					Headloss at indicated depths, cm				
				11 cm	19 cm	29 cm	41 cm	68 cm	11 cm	19 cm	29 cm	41 cm	68 cm
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1a	5.0	0.50	10.00	5.30	5.00	4.75	-	1.75	3.6	5.8	8.5	11.9	16.8
		2.00	9.50	4.70	4.00	2.50	2.15	1.55	6.2	9.5	12.2	15.8	22.0
		3.50	10.50	5.50	-	2.70	2.25	1.80	7.6	10.3	13.0	16.5	22.3
		5.50	9.25	7.60	2.15	1.80	1.60	1.30	11.3	14.2	17.0	20.5	26.1
		7.50	10.50	5.80	4.00	3.50	2.80	1.60	15.8	18.9	21.3	24.5	29.8
		9.50	10.25	8.00	3.80	2.80	1.55	1.25	21.8	25.0	27.6	30.5	35.8
		12.00	10.00	8.00	3.30	3.20	1.90	1.70	31.0	35.3	38.0	41.3	47.2
1b	5.0	0.50	11.00	10.00	-	2.25	2.30	1.80	4.8	7.4	10.6	14.4	19.2
		2.00	10.50	4.20	3.20	2.80	2.30	1.40	6.3	9.0	11.9	15.0	21.0
		3.50	10.00	3.80	3.70	3.40	2.50	1.90	8.1	10.5	13.1	16.0	21.5
		5.50	9.50	8.00	3.10	2.80	1.50	1.45	12.9	15.6	18.4	21.4	26.8
		7.50	10.00	4.50	3.80	1.80	1.70	-	17.1	20.1	22.8	25.7	31.3
		9.50	10.00	7.00	3.30	1.70	-	1.10	24.4	26.7	31.0	34.3	40.1
		12.00	10.25	13.50	8.30	2.80	1.80	1.60	34.8	38.9	41.8	45.0	50.7
1c	5.0	0.50	9.50	6.00	4.60	3.50	1.80	1.40	3.8	6.0	11.5	14.7	18.1
		2.00	10.00	5.30	3.50	-	3.00	0.85	5.5	7.5	10.3	15.9	20.2
		3.50	10.25	5.20	3.40	2.60	1.75	1.00	8.3	11.1	13.8	17.9	24.0
		5.50	9.50	8.00	4.20	3.60	2.40	1.60	13.8	16.6	19.4	22.4	27.9
		7.50	10.50	20.00	4.40	2.60	1.20	1.20	21.1	24.7	27.5	30.8	36.4
		9.50	10.00	14.50	3.80	2.40	2.30	1.40	28.1	31.9	34.7	38.4	43.9
		12.00	9.50	11.00	4.20	2.30	1.70	1.20	42.9	47.5	50.4	54.3	58.7

Contd...

Table B2 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
2a	5.0	0.50	24.50	13.00	3.60	3.00	1.80	1.70	5.0	8.0	11.2	13.3	20.1
		2.00	21.00	22.00	3.40	2.60	1.60	1.40	19.3	22.5	25.1	28.1	35.3
		3.50	23.00	16.00	4.50	2.20	2.10	0.75	39.7	43.0	45.5	48.2	56.8
		5.00	22.50	40.00	9.00	3.30	2.10	1.10	70.0	74.1	76.5	79.0	84.5
		6.50	25.00	30.00	7.50	2.00	1.60	1.00	111.7	118.8	122.3	126.4	133.7
2b	5.0	0.50	24.00	3.50	2.00	1.50	1.10	0.75	4.1	6.0	7.4	10.0	14.6
		2.00	22.00	4.70	2.20	1.80	1.70	0.50	13.0	15.0	17.1	19.6	24.1
		3.50	21.50	13.00	5.00	2.00	-	0.80	27.0	30.0	32.2	35.5	39.8
		5.00	26.00	27.00	8.10	1.60	1.20	0.85	44.3	49.0	51.9	55.0	61.0
		6.50	27.00	33.00	16.00	2.50	1.90	0.65	62.1	68.5	71.5	74.7	80.0
2c	5.0	0.50	23.00	7.00	5.60	4.40	3.70	3.00	4.2	6.0	8.0	11.0	16.3
		2.00	22.50	7.80	3.20	2.20	2.00	1.40	12.5	14.8	17.0	19.8	26.7
		3.50	24.00	30.00	4.80	2.60	2.10	1.20	26.8	29.5	31.7	34.6	41.0
		5.00	25.00	30.00	4.70	2.10	1.60	1.10	47.3	51.2	54.0	56.3	62.8
		6.50	24.50	50.00	13.00	2.70	2.20	1.90	75.0	80.2	81.6	85.5	90.8
3a	7.5	0.50	9.50	3.50	3.30	2.30	0.75	0.50	6.4	10.0	13.8	18.5	27.6
		2.00	10.25	2.80	2.50	2.00	0.80	0.40	12.3	16.5	21.2	26.1	35.8
		3.50	10.75	5.40	5.00	1.70	1.20	0.50	18.3	23.1	27.3	32.0	40.3
		5.50	9.75	8.80	2.60	1.70	0.60	0.55	31.4	37.5	41.0	46.2	54.3
		8.00	9.50	30.00	3.20	1.20	0.50	0.35	59.9	69.0	73.9	78.4	86.4
3b	7.5	0.50	9.00	2.80	2.80	2.60	2.20	1.80	9.4	12.6	16.8	21.9	30.2
		2.00	9.50	1.80	1.30	1.20	1.00	0.35	16.9	20.2	23.3	27.3	34.8
		3.50	10.25	3.10	1.20	0.55	0.50	0.45	23.9	31.5	34.8	38.5	45.4
		5.50	9.00	4.00	1.40	1.10	0.50	0.40	37.8	52.3	55.6	59.3	68.2
		8.00	10.00	5.20	1.80	0.65	0.45	0.45	75.8	82.7	86.9	91.1	98.7

Contd...

Table B2 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
3c	7.5	0.50	10.00	13.00	9.50	1.10	0.70	0.50	6.6	9.8	13.5	17.9	26.6
		2.00	11.00	6.80	3.30	2.40	2.20	1.10	10.5	14.2	17.9	22.2	30.0
		3.50	11.50	5.70	3.90	0.80	0.80	0.50	14.7	19.0	23.0	27.4	35.2
		5.50	10.50	6.80	4.20	0.80	0.50	0.40	24.0	28.9	33.0	37.2	44.4
4a	7.5	0.50	22.00	4.70	2.70	1.20	0.60	0.45	10.9	15.8	20.9	26.5	39.6
		1.50	24.00	9.00	3.00	1.20	0.75	0.45	25.0	30.4	34.3	39.5	49.2
		2.50	25.50	22.00	3.10	1.20	0.55	0.45	42.9	52.3	57.3	61.8	72.2
		3.50	25.00	17.00	6.90	1.20	1.20	0.50	62.3	76.5	82.3	87.4	97.3
		5.00	26.00	17.00	9.00	1.80	0.70	0.40	89.2	101.0	117.4	122.4	132.3
4b	7.5	0.50	23.00	2.80	2.60	-	1.20	1.00	5.5	8.1	11.2	15.2	26.1
		1.50	24.50	5.80	3.80	2.10	2.00	0.70	10.9	14.8	19.1	24.4	36.6
		2.50	25.50	10.00	4.65	3.00	2.70	0.95	19.1	24.3	29.5	35.5	50.5
		3.50	25.00	15.00	4.00	-	1.70	0.75	27.5	33.6	38.8	44.6	57.6
		5.00	24.50	20.00	4.20	4.00	1.30	1.00	40.9	48.1	53.1	58.3	70.1
4c	7.5	0.50	24.80	3.80	2.80	-	2.00	0.90	7.4	10.9	15.2	19.9	29.6
		1.50	23.50	8.00	4.30	1.90	1.80	0.70	14.2	18.3	22.7	27.6	37.1
		2.50	24.00	-	1.40	7.50	1.00	0.75	20.9	25.3	29.3	34.0	42.8
		3.50	23.50	16.00	4.00	2.00	1.60	0.75	24.1	29.3	34.4	39.9	49.9
		5.00	22.00	30.00	3.50	3.50	2.60	0.80	44.0	50.1	54.9	59.6	68.3
5a	10.0	0.50	13.50	2.80	2.30	1.90	1.60	0.85	8.3	13.4	19.3	26.1	39.6
		2.00	10.00	3.60	1.80	1.70	1.50	0.90	12.6	18.4	24.5	31.7	45.8
		3.50	11.00	10.00	3.40	2.40	4.00	1.00	16.5	22.4	28.1	34.8	47.7
		5.50	10.25	9.20	3.00	3.00	2.30	0.60	28.2	36.5	43.6	51.6	68.0
		8.00	10.00	8.00	2.60	1.60	2.00	1.25	41.6	49.3	55.3	61.6	72.9
5b	10.0	0.50	12.00	2.50	2.00	1.60	1.30	1.00	7.9	11.9	16.4	22.0	32.4
		2.00	10.50	2.30,	2.10	2.70	1.60	1.10	14.2	19.9	25.9	33.4	47.0
		3.50	9.50	3.20	1.60	1.20	1.40	0.90	20.5	26.1	31.7	38.2	50.0
		5.50	10.25	5.60	2.25	2.00	1.60	0.95	30.8	36.7	42.4	48.7	60.1
		8.00	10.00	6.60	2.10	2.00	1.80	0.75	41.5	48.4	53.9	60.2	70.2

Contd...

Table B2 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
5c	10.0	0.50	9.50	3.25	2.30	3.00	1.20	1.00	9.5	14.0	19.7	26.1	39.1
		2.00	11.50	3.50	2.00	1.80	1.10	0.90	15.4	21.1	26.7	33.6	46.5
		3.50	11.00	7.00	2.00	1.80	1.50	0.85	20.3	26.1	31.6	38.6	49.0
		5.50	10.00	9.80	2.50	2.60	1.10	0.90	33.9	41.1	48.0	54.3	66.1
		8.00	10.50	7.50	2.60	3.20	2.40	0.80	51.3	59.5	65.8	72.1	83.5
6a	10.0	0.50	25.00	4.30	4.60	2.00	0.90	0.85	9.3	13.9	19.0	24.7	36.9
		1.25	23.50	15.00	3.10	2.40	2.10	0.80	16.5	22.1	27.5	34.5	43.9
		2.00	23.00	19.00	4.50	3.20	1.20	0.80	25.1	31.6	37.3	43.8	55.7
		3.00	25.00	8.80	5.40	2.40	1.10	0.80	40.0	48.3	54.6	61.0	73.0
		4.00	22.50	30.00	8.25	2.25	1.40	0.70	56.1	66.7	73.0	79.4	90.1
6b	10.0	0.50	22.00	6.20	2.60	1.30	1.10	0.80	8.3	12.2	16.7	22.1	32.5
		1.25	25.00	11.00	4.00	3.80	1.20	0.80	11.2	15.9	20.8	26.1	37.1
		2.00	26.50	11.00	3.80	1.80	1.30	0.80	20.4	24.9	31.0	36.7	47.9
		3.00	25.50	28.00	4.60	2.00	0.85	0.90	34.4	41.1	46.5	52.1	62.8
		4.00	26.25	30.00	6.40	2.80	0.95	0.75	51.8	61.1	67.7	73.0	87.0
6c	10.0	0.50	26.00	10.50	4.70	3.00	1.60	1.10	10.1	15.9	22.0	29.2	41.6
		1.25	24.00	9.70	3.50	1.30	1.00	0.80	16.2	21.8	28.1	35.1	46.5
		2.00	23.50	9.20	3.50	2.00	1.40	0.85	26.7	34.9	41.9	49.1	51.7
		3.00	25.50	40.00	-	2.75	1.60	0.75	42.5	52.9	60.1	67.2	79.7
		4.00	25.00	35.00	8.30	3.60	0.90	0.75	68.8	84.5	92.4	100.1	111.8

Table B3 - Turbidity and headloss data for stone-dust laboratory filter (Media size: d_m 0.65 mm; e.s. 0.62 mm; u.c. 1.04)

Filter	Filtration rate (V_o) m/h	Time hr	Influent turbidity (c_o) NTU	Turbidity at indicated depths (c), NTU					Headloss at indicated depths, cm				
				11 cm	19 cm	29 cm	41 cm	68 cm	11 cm	19 cm	29 cm	41 cm	68 cm
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1a	5.0	0.50	11.50	2.30	1.50	1.10	0.75	0.60	4.2	6.0	8.3	10.6	15.4
		2.00	10.00	2.10	1.30	0.65	0.40	0.35	6.6	8.6	11.0	13.6	18.8
		3.50	9.50	3.10	1.10	0.75	0.50	0.40	8.7	10.5	12.6	14.8	19.4
		6.00	10.00	2.80	0.85	0.80	0.55	0.45	13.6	16.9	19.1	21.3	26.0
		9.00	9.50	2.80	0.85	0.80	0.55	0.45	23.0	25.6	27.5	29.7	33.9
		12.00	10.00	10.50	2.10	1.50	0.70	0.40	35.0	38.2	40.4	42.8	47.0
1b	5.0	0.50	10.50	3.00	2.80	1.40	0.90	0.75	4.2	6.2	8.8	11.3	16.7
		2.00	9.50	1.60	0.90	1.00	0.75	0.35	5.7	7.6	9.8	12.2	17.4
		3.50	9.50	2.20	1.70	0.80	0.75	0.40	8.3	10.3	12.5	14.8	19.4
		6.00	10.00	5.00	2.80	1.20	0.85	0.45	12.7	15.0	17.1	19.2	23.5
		9.00	10.50	5.30	3.50	1.20	1.00	0.55	24.2	26.7	28.9	31.3	35.4
		12.00	10.00	13.00	2.65	1.20	1.00	0.60	35.7	38.9	41.3	44.2	48.6
1c	5.0	0.50	10.00	4.10	1.80	0.90	0.85	0.70	4.2	6.1	8.4	10.8	15.5
		2.00	10.00	2.40	1.30	1.10	0.75	0.50	7.8	10.6	13.3	16.2	21.8
		3.50	9.80	2.30	1.40	0.80	0.75	0.55	10.9	13.5	15.8	18.5	23.2
		6.00	10.50	4.90	1.60	0.85	0.75	0.60	20.2	23.2	25.7	28.7	33.7
		9.00	9.50	4.00	0.95	0.65	0.80	0.40	32.3	35.2	37.5	40.2	44.2
		12.00	10.00	5.60	1.40	0.70	0.60	0.45	49.5	53.3	55.7	58.3	62.8

Contd...

Table B3 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
2a	5.0	0.50	25.00	2.60	1.70	1.60	0.75	0.40	4.1	5.5	7.2	9.0	13.1
		2.00	23.50	4.40	2.80	0.90	0.70	0.50	10.6	12.1	13.7	15.5	19.2
		4.00	23.00	6.20	4.30	1.00	0.90	0.45	29.5	31.8	33.6	35.7	40.2
		6.00	24.00	8.70	4.50	0.90	0.60	0.50	57.4	60.2	62.1	64.4	68.2
		8.00	25.00	16.00	4.70	0.90	0.60	0.45	99.7	104.1	106.4	109.7	112.5
2b	5.0	0.50	23.50	4.00	3.00	1.30	1.10	0.60	4.3	5.9	7.4	9.3	13.0
		2.00	22.50	5.70	1.70	1.60	0.65	0.50	12.7	14.4	16.0	17.8	21.4
		4.00	22.50	8.00	2.80	0.80	0.60	0.40	30.8	37.0	38.9	41.0	44.3
		6.00	26.00	13.00	9.50	0.90	0.75	0.30	88.5	92.7	94.9	97.1	100.5
		8.00	25.50	25.00	5.60	0.75	0.45	0.50	160.1	166.5	167.6	168.8	171.0
2c	5.0	0.50	27.50	6.00	2.40	0.90	0.80	0.50	4.3	5.9	7.3	9.6	14.9
		2.00	26.50	5.30	2.80	0.90	0.85	0.45	10.6	12.6	14.5	16.6	21.8
		4.00	25.50	6.60	2.80	0.90	0.75	0.40	24.6	27.5	29.6	31.8	36.7
		6.00	24.50	7.00	2.10	0.75	0.50	0.40	54.5	59.5	61.8	64.3	69.2
		8.00	24.00	9.40	7.80	1.70	0.85	0.45	84.8	92.9	94.6	98.1	101.9
3a	7.5	0.50	10.50	2.10	1.50	1.40	0.75	0.50	4.9	7.2	10.1	13.5	20.0
		1.50	11.00	2.20	1.90	1.00	0.80	0.75	7.4	10.3	13.9	17.4	24.6
		3.00	9.00	4.50	1.90	1.70	0.80	0.50	11.3	15.0	18.6	22.5	30.0
		5.00	9.50	8.90	3.80	1.60	1.30	0.55	13.7	21.8	25.5	29.5	36.5
		7.00	10.00	10.50	3.30	3.30	0.60	0.50	24.1	28.9	32.5	36.2	42.8
		10.00	9.00	12.50	6.80	1.50	0.60	0.45	37.3	43.0	47.0	50.8	57.3
3b	7.5	0.50	11.00	1.50	0.85	0.70	0.60	0.35	6.0	8.7	11.7	15.1	21.7
		1.50	9.50	5.30	2.30	0.65	0.60	0.30	8.0	10.8	14.9	17.2	23.9
		3.00	10.50	2.40	1.00	0.80	0.60	0.35	11.0	15.3	17.5	20.7	27.3
		5.00	10.50	5.00	2.00	0.75	0.45	0.35	18.1	21.7	24.6	27.7	33.9
		7.00	9.50	14.00	1.90	0.70	0.60	0.40	27.5	31.8	34.8	37.8	43.3
		10.00	8.50	14.50	8.20	0.90	0.50	0.45	55.5	60.1	63.5	66.6	72.4

Contd...

Table B3 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
3c	7.5	0.50	11.00	2.10	1.40	0.75	0.60	0.50	6.4	8.5	11.0	13.0	17.5
		1.50	9.50	2.20	1.00	0.90	0.80	0.45	10.0	12.4	14.9	17.5	22.0
		3.00	10.00	3.40	1.70	1.10	0.65	0.45	13.0	16.3	19.5	22.8	28.9
		5.00	11.00	8.90	4.40	1.40	0.80	0.50	31.0	35.1	38.8	42.7	49.0
		7.00	9.50	8.90	8.00	1.30	0.85	0.45	47.0	51.4	55.0	58.4	64.0
		10.00	10.00	16.00	7.20	1.00	1.10	0.50	96.1	100.0	105.6	108.8	113.9
4a	7.5	0.50	25.00	6.20	3.30	2.50	1.00	0.50	7.1	9.7	12.7	15.7	22.3
		1.50	24.50	11.00	5.30	1.15	0.90	0.50	18.0	21.4	24.7	28.2	35.1
		3.00	25.50	19.00	6.10	2.50	1.50	0.60	36.7	41.6	45.2	48.7	55.3
		4.50	26.00	23.00	6.10	2.00	1.50	0.60	67.9	75.8	79.8	83.2	86.9
		6.00	24.00	28.00	18.00	1.90	1.20	0.60	97.9	109.7	114.1	117.7	123.2
4b	7.5	0.50	24.50	5.40	3.20	1.20	1.30	0.50	6.5	9.1	11.9	15.0	21.6
		1.50	25.00	6.50	3.00	1.00	0.80	0.60	11.8	15.0	18.1	21.3	26.8
		3.00	26.50	7.90	3.60	1.10	1.10	0.45	24.6	28.9	32.3	35.7	42.2
		4.50	25.00	24.00	11.50	3.10	1.80	0.60	45.7	52.7	56.5	60.0	66.9
		6.00	24.00	26.00	11.00	3.20	1.10	0.50	64.2	72.6	78.0	81.8	87.8
4c	7.5	0.50	23.00	7.80	3.50	1.50	1.10	0.65	7.1	8.9	11.6	14.5	20.4
		1.50	24.50	7.10	2.80	1.15	0.80	0.60	17.3	20.0	22.5	25.5	31.5
		3.00	24.00	13.00	11.00	1.10	0.80	0.55	37.5	41.0	44.0	47.2	53.3
		4.50	26.00	13.00	6.60	1.50	0.80	0.60	69.3	74.2	77.0	80.1	85.3
		6.00	25.00	32.00	20.00	2.25	0.75	0.45	100.5	108.0	111.2	114.3	119.4
5a	10.0	0.50	10.50	2.40	1.30	0.90	0.80	0.50	6.9	10.0	13.7	18.3	26.5
		1.50	10.00	2.80	1.60	0.80	0.60	0.40	10.3	14.0	17.7	22.0	29.9
		3.00	11.00	2.60	1.80	1.20	1.00	0.50	14.7	19.7	24.4	29.7	39.0
		4.50	8.50	1.90	1.70	1.00	0.60	0.60	26.8	32.0	36.4	40.9	49.0
		6.00	9.50	3.70	1.80	0.80	0.50	0.40	35.6	41.9	56.4	61.3	69.6

Contd.

Table B3 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
5b	10.0	0.50	8.00	2.40	2.40	2.00	0.75	0.60	7.0	10.4	14.4	19.4	28.1
		1.50	9.00	3.30	1.80	1.10	0.50	0.45	10.6	14.4	18.8	23.4	32.9
		3.00	8.50	3.80	3.40	0.80	0.65	0.50	17.3	22.2	26.3	32.3	41.9
		5.00	10.00	15.00	5.40	2.40	0.80	0.50	28.1	33.6	38.5	43.5	51.8
		7.50	10.50	16.00	11.00	2.10	0.60	0.40	42.9	50.3	55.4	60.3	68.6
5c	10.0	0.50	9.00	3.00	1.80	1.10	0.90	0.65	7.4	11.0	15.3	20.4	30.1
		1.50	10.00	2.90	2.60	1.00	0.75	0.60	10.0	14.1	18.7	23.9	33.3
		3.00	10.00	3.00	1.80	1.40	1.00	0.50	14.1	18.7	23.4	28.7	38.5
		5.00	10.50	9.20	5.90	1.90	3.00	0.45	20.4	25.5	30.0	35.2	44.0
		7.50	9.50	18.00	15.00	2.30	1.70	0.45	43.2	50.2	55.5	61.0	70.0
6a	10.0	0.50	24.00	11.50	5.40	2.00	1.60	0.80	9.3	13.0	17.3	21.3	30.3
		1.25	25.50	7.80	6.40	2.10	1.60	0.45	15.1	19.2	23.4	28.6	35.3
		2.00	25.50	15.20	10.00	2.80	1.60	0.45	32.2	38.8	45.0	49.3	57.7
		3.00	23.00	21.00	15.00	2.70	2.40	0.45	52.7	62.7	68.9	74.6	83.3
		4.00	22.00	18.00	10.00	2.40	1.60	0.60	79.5	92.9	99.9	105.1	113.1
6b	10.0	0.50	26.50	9.00	8.00	3.70	2.50	0.80	6.7	10.2	14.3	19.2	29.0
		1.25	25.00	7.00	4.10	1.50	1.20	0.75	9.6	13.9	18.3	23.1	31.8
		2.00	22.50	5.70	3.40	1.60	1.10	0.65	17.5	23.3	28.2	33.4	42.3
		3.00	24.00	21.00	10.50	1.70	1.00	0.60	29.7	37.3	42.8	48.3	57.4
		4.00	23.50	26.00	11.00	3.20	1.40	0.60	45.2	55.3	61.4	67.2	76.5
6c	10.0	0.50	23.50	5.60	3.20	1.40	1.20	1.10	10.6	13.8	17.2	21.7	30.2
		1.25	25.00	5.90	5.10	1.20	0.90	0.55	21.1	25.1	28.9	33.3	41.4
		2.00	24.00	11.70	10.60	2.00	1.80	0.75	36.9	41.7	45.5	50.0	57.7
		3.00	26.00	11.20	7.00	1.60	1.20	0.60	63.9	70.9	75.2	79.9	87.7
		4.00	24.00	15.50	9.80	2.20	1.10	0.50	104.2	115.4	119.8	124.2	131.8

Table C1 - Turbidity and headloss data for sand laboratory filter
(Media size: d_m 0.46 mm; e.s. 0.44 mm; u.c. 1.09)

Filter run	Filtration rate (V_o) m/h	Time hr	Influent turbidity (c_o) NTU	Turbidity at indicated depths (c), NTU					Headloss at indicated depths, cm				
				11 cm	19 cm	29 cm	41 cm	68 cm	11 cm	19 cm	29 cm	41 cm	68 cm
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(8)	(10)	(11)	(12)	(13)	(14)
		0.50	10.00	1.80	1.70	0.90	0.70	0.50	7.4	11.8	17.2	23.6	34.7
		2.00	10.00	1.00	1.10	1.00	0.85	0.55	15.2	19.4	24.1	29.8	33.3
		3.50	10.50	1.00	0.90	0.60	1.00	0.55	23.8	28.1	33.1	39.1	48.8
1a	5.0	5.50	10.00	1.70	1.30	1.25	0.75	0.55	40.0	44.9	50.3	56.5	66.4
		7.00	9.50	7.60	1.55	1.25	1.25	0.75	54.8	60.1	65.3	71.6	81.6
		9.50	9.80	2.90	1.15	0.80	1.00	0.50	87.4	93.7	99.3	105.7	115.9
		12.00	10.00	6.60	2.00	0.80	0.90	0.90	126.3	133.4	139.0	145.2	155.2
		0.50	11.50	2.00	1.50	1.25	1.60	0.80	8.8	13.2	18.7	25.1	35.4
		2.00	10.20	2.60	1.40	1.25	1.50	0.65	15.4	20.2	25.3	31.4	40.7
		3.50	9.00	2.10	1.10	1.00	1.05	0.60	23.6	28.1	32.6	38.1	46.1
1b	5.0	5.50	10.00	2.55	3.50	0.85	-	0.85	43.2	48.1	53.0	58.8	67.6
		7.00	11.00	6.00	1.65	1.10	2.95	0.80	57.1	62.0	66.0	72.1	80.1
		9.50	9.50	2.70	1.10	1.00	0.80	0.80	85.9	90.8	95.1	100.3	107.7
		12.00	11.00	5.50	1.70	1.20	1.10	0.80	119.4	124.9	129.6	135.0	143.0
		0.50	12.00	2.90	-	2.40	2.00	0.60	8.5	13.6	19.7	26.4	37.6
		2.00	10.50	1.50	1.00	0.90	0.80	0.50	14.2	20.2	26.5	35.2	44.2
		3.50	9.50	2.60	1.10	0.80	0.40	0.40	20.9	27.1	33.9	40.6	52.2
1c	5.0	5.50	11.50	5.50	2.10	0.60	0.50	0.40	40.5	47.1	53.3	59.8	70.7
		7.00	10.00	1.80	1.20	1.00	0.70	0.35	64.3	71.1	77.8	84.5	95.3
		9.50	11.50	7.00	1.40	1.30	0.70	0.70	115.4	123.1	129.6	135.9	145.9
		12.00	10.00	4.80	1.30	1.00	0.50	0.40	134.1	141.8	148.4	153.9	163.4

Contd...

Table C1 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
2a	5.0	0.50	26.50	2.40	2.20	2.00	1.00	0.70	9.0	12.9	17.6	23.5	33.3
		2.00	24.00	8.70	2.00	0.90	0.85	0.80	26.0	29.9	34.3	35.6	49.1
		3.50	26.00	14.00	3.20	1.80	0.80	0.75	52.3	56.9	61.4	67.0	76.7
		5.50	25.50	9.20	2.70	2.60	7.20	1.10	96.5	101.3	105.4	110.0	117.8
		6.75	25.00	18.00	6.60	5.60	3.60	3.60	140.3	147.1	152.3	158.4	169.0
2b	5.0	0.50	24.50	2.60	3.00	1.80	2.00	0.80	7.6	10.5	14.7	19.7	28.8
		2.00	23.00	5.40	4.60	2.80	1.60	0.90	19.5	23.5	28.0	33.5	42.3
		3.50	23.50	5.10	2.10	9.80	1.70	0.90	41.7	45.6	49.7	54.6	62.3
		5.50	23.00	8.20	2.20	5.60	2.00	1.10	80.7	84.8	88.8	93.5	101.0
		6.75	23.00	8.50	1.80	1.80	1.20	1.10	112.5	117.2	121.5	126.4	132.8
2c	5.0	0.50	22.00	4.10	4.10	2.10	7.00	1.80	8.0	11.7	16.2	21.7	30.4
		2.00	25.50	13.50	2.70	2.80	2.20	2.00	17.5	22.2	27.0	33.3	43.5
		3.50	26.50	10.50	4.70	3.80	2.20	1.60	36.7	42.8	48.7	55.2	65.1
		5.50	25.50	22.00	13.00	2.20	1.70	1.30	68.4	74.3	79.2	84.7	92.7
3a	7.5	0.50	12.00	1.50	1.40	1.50	1.50	0.80	14.1	20.3	27.7	36.4	51.4
		2.00	11.00	2.60	1.70	1.20	1.00	0.75	24.0	33.4	40.9	49.6	64.2
		3.50	10.00	3.60	3.00	1.40	0.90	0.60	32.2	39.1	46.5	55.0	69.0
		5.00	11.00	2.60	1.30	1.20	0.80	0.50	54.9	62.0	69.2	77.3	90.7
		6.50	9.50	9.20	5.20	0.90	0.80	0.50	80.4	89.1	97.4	106.6	121.9
		8.00	10.00	8.50	2.60	1.50	0.75	0.60	107.6	110.9	119.7	129.5	145.5
		9.50	10.00	4.30	2.60	1.50	0.80	0.80	119.7	129.3	137.2	145.5	159.6
3b	7.5	0.50	10.00	2.00	1.50	1.40	1.20	0.90	8.7	18.3	25.7	35.0	49.0
		2.00	9.50	2.60	2.40	1.40	2.80	0.75	22.0	29.5	39.5	51.6	70.7
		3.50	10.00	5.10	1.80	1.70	1.70	0.50	29.9	37.3	46.1	56.4	72.6
		5.00	9.00	3.90	2.75	1.90	1.10	0.90	41.0	48.8	57.5	67.8	73.8
		6.50	10.00	2.30	1.60	1.00	0.70	0.50	51.5	59.3	67.9	77.9	93.3
		8.00	9.50	2.40	1.80	1.70	1.25	0.75	68.3	76.4	84.8	94.8	110.2
		9.50	9.00	10.20	4.40	1.80	2.00	0.90	84.8	93.3	101.8	111.0	126.0

Contd...

Table C1 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
5b	10.0	0.50	10.00	11.50	3.30	3.50	1.80	1.10	17.6	26.6	37.2	50.3	75.9
		1.50	10.00	7.00	2.90	2.70	1.40	1.30	30.9	41.0	53.3	68.1	95.9
		2.50	11.00	11.50	4.80	4.40	1.30	1.00	51.0	63.5	75.7	90.3	116.9
		4.00	11.50	12.00	3.90	8.00	1.30	0.80	99.1	106.5	119.1	133.1	159.2
		5.50	12.00	11.00	5.30	2.80	1.70	1.60	122.8	139.9	151.9	164.7	188.2
		7.00	10.80	20.00	8.50	8.00	2.20	1.20	161.4	180.4	192.3	204.6	230.0
5c	10.0	0.50	11.50	17.00	6.60	5.40	2.10	2.00	16.2	24.6	34.9	47.8	69.3
		1.50	9.50	4.90	2.40	-	1.30	1.20	22.7	31.7	42.6	52.6	77.4
		2.50	9.50	10.00	4.50	3.80	2.00	1.50	29.6	38.7	48.9	61.1	81.0
		4.00	9.00	5.70	3.00	2.60	2.40	1.10	51.7	61.5	72.6	85.8	107.7
		5.50	10.00	7.30	4.00	2.50	1.80	1.10	81.6	92.5	103.7	116.2	138.2
		7.00	10.25	18.00	5.00	3.00	2.30	1.80	120.6	134.5	148.0	162.5	187.2
6a	10.0	0.50	25.50	13.00	5.00	4.80	1.80	1.20	19.6	28.5	38.9	52.3	75.6
		1.25	20.50	22.00	7.40	-	1.50	1.20	31.8	51.9	62.9	76.2	99.2
		2.00	22.00	13.50	5.00	2.20	1.80	1.30	72.5	85.6	94.9	118.3	131.0
		2.75	24.00	15.00	4.10	1.90	1.75	1.10	102.5	115.2	125.8	138.2	159.0
		3.50	23.00	18.00	4.60	3.20	1.80	1.30	146.5	156.0	171.3	185.0	208.0
6b	10.0	0.50	21.00	6.20	2.30	1.90	1.20	0.70	26.4	36.0	47.7	72.0	88.0
		1.25	23.00	3.00	1.80	-	1.20	0.75	62.9	72.1	82.3	95.2	116.0
		2.00	22.50	15.00	4.80	4.50	2.20	0.90	101.3	114.0	125.6	139.0	161.9
		2.75	25.50	12.00	2.60	1.70	1.10	0.90	134.9	147.6	157.0	166.8	184.1
		3.50	23.00	13.50	4.00	2.20	2.20	1.10	171.4	186.8	195.5	204.5	225.0
6c	10.0	0.50	21.50	7.80	4.20	-	1.70	1.20	24.3	34.5	45.5	58.8	80.0
		1.25	22.0	8.30	7.00	3.10	2.00	1.60	37.0	46.8	57.6	70.5	92.0
		2.00	21.50	4.80	2.60	2.40	1.80	1.30	51.6	61.7	72.6	84.8	105.1
		2.75	24.50	17.00	9.00	4.70	1.90	1.20	81.6	92.5	103.3	115.0	134.0
		3.50	26.00	17.50	5.00	3.20	-	1.20	113.7	127.3	140.2	151.7	172.0

Table C2 - Turbidity and headloss data for sand laboratory filter (Media size: d_m 0.54 mm; e.s. 0.53 mm, u.c. 1.09)

Filter run	Filtration rate (V_o) m/h	Time hr	Influent turbidity (c_o) NTU	Turbidity at indicated depths (c), NTU					Headloss at indicated depths, cm				
				11 cm	19 cm	29 cm	41 cm	68 cm	11 cm	19 cm	29 cm	41 cm	68 cm
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
		0.50	10.00	20.00	9.00	-	2.40	1.80	8.3	13.2	18.7	26.0	35.7
		2.00	9.50	-	4.50	4.40	2.60	1.60	10.0	15.7	21.8	28.9	38.0
		3.50	10.50	6.90	3.30	-	1.60	1.50	12.5	17.5	23.2	29.5	39.0
1a	5.0	5.50	9.25	6.50	3.80	2.90	1.75	1.40	19.7	23.7	29.5	35.7	44.7
		7.50	10.50	8.20	5.00	4.20	2.50	1.60	25.6	31.6	37.4	43.4	52.2
		9.50	10.25	18.00	3.80	-	1.00	1.40	36.7	43.9	50.6	56.9	66.8
		12.00	10.00	11.00	4.20	3.30	1.80	1.50	49.8	57.8	64.4	70.8	80.7
		0.50	11.00	12.00	7.80	-	2.50	2.60	8.9	13.6	19.8	23.4	28.9
		2.00	10.50	3.90	3.10	6.00	1.80	1.50	11.4	16.4	21.3	24.8	30.3
		3.50	10.00	4.70	3.40	6.25	2.25	1.75	12.2	16.7	20.9	26.9	34.8
1b	5.0	5.50	9.50	13.00	5.90	-	1.90	1.60	12.7	22.4	26.8	32.2	40.9
		7.50	10.00	6.30	5.40	3.00	1.70	1.65	23.0	28.4	33.2	39.1	47.3
		9.50	10.00	10.20	3.60	3.20	1.50	1.20	30.5	36.6	41.5	47.2	55.6
		12.00	10.25	8.80	8.00	-	2.00	1.80	46.4	53.4	59.1	65.2	73.4
		0.50	9.50	10.00	4.50	2.25	1.70	1.45	4.5	12.8	19.3	27.2	39.8
		2.00	10.00	10.00	5.90	2.25	1.60	1.10	9.6	14.9	20.1	27.2	41.8
		3.50	10.25	13.00	7.80	3.60	1.65	1.00	18.6	24.9	30.8	38.5	52.2
1c	5.0	5.50	9.50	20.00	7.60	2.25	2.10	1.70	28.2	34.7	40.0	46.0	58.3
		7.50	10.50	30.00	3.80	2.80	2.20	1.40	38.7	46.5	51.9	58.5	69.6
		9.50	10.00	30.00	13.00	2.70	1.50	1.50	48.5	59.0	64.7	71.9	83.4
		12.00	9.50	40.00	11.20	1.70	1.35	1.20	65.5	79.7	85.6	92.1	103.4

Contd...

Table C2 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
2a	5.0	0.50	24.50	30.00	18.00	9.20	2.20	2.00	15.6	21.5	25.5	37.5	48.9
		2.00	21.00	28.00	5.00	3.70	2.00	1.90	36.9	46.5	51.0	62.4	72.0
		3.50	23.00	32.00	9.20	2.25	1.40	0.90	67.8	82.8	87.3	92.1	101.2
		5.00	22.50	40.00	18.00	3.40	2.60	1.10	118.0	132.0	136.5	141.1	150.0
		6.50	25.00	45.00	35.00	3.10	1.60	1.10	170.6	187.3	194.0	199.3	209.3
2b	5.0	0.50	24.00	21.00	11.00	2.80	1.25	0.75	11.8	16.4	22.2	30.4	38.7
		2.00	22.00	30.00	4.20	3.00	2.00	0.60	20.0	32.0	35.2	52.5	61.5
		3.50	21.50	40.00	5.30	-	2.10	0.80	51.7	59.2	64.5	72.5	79.6
		5.00	26.00	37.00	11.50	3.30	1.45	0.90	79.3	92.9	100.5	110.5	119.0
		6.50	27.00	40.00	19.00	2.90	1.10	0.85	94.0	112.3	120.0	128.1	135.0
2c	5.0	0.50	23.00	14.00	7.20	8.00	4.20	3.80	10.0	14.0	17.9	23.0	31.3
		2.00	22.50	12.00	4.00	-	1.50	1.00	32.5	37.8	42.4	48.0	56.2
		3.50	24.00	40.00	7.60	-	2.00	1.90	62.6	68.6	73.4	78.7	86.6
		5.00	25.00	50.00	14.00	2.25	1.75	1.25	98.3	106.8	111.8	116.9	134.6
		6.50	24.50	50.00	19.00	3.80	1.50	1.50	148.6	153.4	165.0	170.0	178.0
3a	7.5	0.50	9.50	7.70	4.40	-	1.10	0.60	12.4	19.0	26.2	35.1	49.1
		2.00	10.25	6.10	3.30	1.30	0.80	0.70	21.7	27.0	35.6	43.5	55.5
		3.50	10.75	7.00	4.00	1.70	1.50	0.50	34.3	40.8	50.0	57.8	69.8
		5.50	9.75	8.30	3.80	0.80	0.75	0.35	59.0	69.6	79.8	85.5	97.0
		8.00	9.50	20.00	11.00	0.70	0.70	0.40	104.3	120.4	129.0	136.5	147.6
3b	7.5	0.50	9.00	4.40	3.00	2.60	2.30	1.80	15.5	21.2	28.4	35.9	47.6
		2.00	9.50	3.20	1.20	0.60	0.50	0.40	23.5	30.8	37.5	44.4	55.4
		3.50	10.25	5.20	2.20	0.70	0.50	0.40	36.4	43.5	50.9	57.2	67.4
		5.50	9.00	20.00	6.20	1.20	0.50	0.40	64.6	71.6	78.3	84.1	93.3
		8.00	10.00	17.00	4.00	0.75	0.50	0.45	108.5	119.6	126.1	131.9	141.1

Contd...

Table C2 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
3c	7.5	0.50	10.00	13.00	18.00	2.80	1.90	0.50	13.2	17.8	25.6	33.8	37.2
		2.00	11.00	20.00	7.50	5.00	2.30	1.80	18.0	26.4	30.5	39.4	57.0
		3.50	11.50	25.00	3.80	1.70	1.80	0.50	25.8	34.3	38.8	52.1	65.8
		5.50	10.50	10.30	4.00	1.90	0.60	0.50	37.6	53.5	58.8	70.4	83.1
4a	7.5	0.50	22.00	9.40	5.50	2.00	0.75	0.40	16.5	17.5	28.7	41.3	54.8
		1.50	24.00	8.00	5.00	1.20	0.75	0.35	36.1	40.9	48.4	59.3	71.3
		2.50	25.50	40.00	30.00	2.30	1.50	0.50	60.1	72.0	85.1	88.1	101.1
		3.50	25.00	30.00	19.00	1.40	0.70	0.40	79.2	95.3	104.4	112.2	123.3
		5.00	26.00	19.00	15.00	2.80	0.85	0.45	109.9	134.4	146.0	153.4	164.3
4b	7.5	0.50	23.00	7.40	6.80	4.90	3.80	0.80	8.0	13.3	18.1	23.9	34.1
		1.50	24.50	7.00	4.80	2.80	1.60	0.70	15.0	17.8	23.5	30.7	43.5
		2.50	25.50	7.80	7.30	3.20	2.30	0.90	23.7	30.6	37.9	44.0	63.5
		3.50	25.00	17.00	7.40	4.50	3.00	0.80	36.7	46.6	54.7	61.6	82.8
		5.00	24.50	16.00	13.00	4.00	2.90	0.85	55.5	66.0	73.8	82.7	97.3
4c	7.5	0.50	24.80	6.80	5.00	5.00	1.90	1.00	8.9	13.6	18.8	25.9	37.4
		1.50	23.50	9.00	3.50	3.40	2.20	0.90	17.2	22.0	29.3	37.1	49.1
		2.50	24.00	18.50	6.50	2.80	3.00	0.90	26.9	33.0	40.2	47.6	59.5
		3.50	23.50	11.50	6.90	5.00	4.00	0.85	40.8	49.2	55.1	62.2	73.7
		5.00	22.00	10.00	5.70	1.90	1.50	0.85	65.6	75.5	82.1	89.1	101.1
5a	10.0	0.50	13.50	6.20	3.80	3.60	3.50	0.90	9.3	15.2	21.3	29.9	44.6
		2.00	10.00	8.80	6.00	1.50	1.50	1.05	17.4	24.1	34.0	45.5	63.2
		3.50	11.00	9.80	6.50	2.70	2.20	1.10	22.3	29.6	38.6	49.2	66.6
		5.50	10.25	10.00	4.50	3.60	3.00	0.70	35.8	44.1	53.3	63.7	80.2
		8.00	10.00	12.00	4.00	1.90	1.80	1.20	53.6	62.6	71.0	80.4	94.8

Contd...

Table C2 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
		0.50	12.00	4.50	2.80	1.50	1.30	0.80	11.5	17.7	25.0	33.7	48.4
		2.00	10.50	3.10	2.80	2.10	1.20	0.90	20.0	27.3	36.0	46.3	62.7
5b	10.0	3.50	9.50	3.60	2.20	2.10	1.60	0.95	27.7	35.0	43.8	53.6	69.2
		5.50	10.25	8.50	8.00	4.30	2.80	1.00	40.9	50.0	58.5	68.2	84.0
		8.00	10.00	14.00	3.30	1.60	1.80	1.10	62.5	73.7	82.3	92.0	105.1
		0.50	9.50	4.00	2.30	2.00	1.30	0.80	13.6	21.3	28.7	38.9	55.4
		2.00	11.50	11.00	3.80	4.50	1.40	0.90	22.8	27.4	35.3	45.1	60.1
5c	10.0	3.50	11.00	16.20	4.00	2.00	1.60	0.85	27.3	34.6	42.8	52.4	66.7
		5.50	10.00	9.40	2.80	3.20	3.40	1.10	45.2	54.6	62.6	72.6	87.0
		8.00	10.50	9.00	6.40	1.75	1.50	0.80	68.1	78.0	86.8	96.3	110.7
		0.50	25.00	5.50	3.40	4.50	2.00	0.80	15.2	22.6	33.4	44.4	62.5
		1.25	23.50	20.00	10.00	4.00	2.20	0.75	18.7	30.3	47.8	58.8	76.4
6a	10.0	2.00	23.00	15.00	6.50	3.00	1.50	0.90	38.1	47.1	56.2	68.4	82.6
		3.00	25.00	14.50	6.80	2.50	3.00	0.75	58.6	69.0	78.3	88.0	102.6
		4.00	22.50	40.00	30.00	2.80	1.70	0.75	82.4	97.4	107.9	118.5	134.2
		0.50	22.00	19.00	5.40	2.70	1.35	0.75	13.0	19.0	26.3	35.6	50.0
		1.25	25.00	9.20	6.00	2.10	1.80	1.00	21.6	29.6	38.3	49.8	65.1
6b	10.0	2.00	26.50	7.20	5.40	2.20	1.00	0.80	32.5	40.3	49.0	59.7	72.6
		3.00	25.50	29.00	7.80	2.80	2.00	0.80	53.3	63.7	72.6	82.1	96.2
		4.00	26.25	26.00	21.00	5.50	2.30	0.75	80.0	89.2	99.2	110.2	122.5
		0.50	26.00	26.00	5.80	-	2.40	1.00	12.1	19.3	26.6	36.3	52.4
		1.25	24.00	10.70	4.80	2.60	1.70	0.80	19.6	27.1	36.6	46.9	63.3
6c	10.0	2.00	23.50	15.50	5.10	3.20	2.10	0.90	35.4	46.0	56.3	67.7	85.6
		3.00	25.50	40.00	20.00	5.20	1.80	0.80	57.5	65.1	75.8	86.3	102.2
		4.00	25.00	24.00	18.70	3.30	1.80	0.80	82.4	95.4	114.2	125.4	141.3

Contd...

Table C3 - Turbidity and headloss data for sand laboratory filter
(Media size: d_m. 0.65 mm; e.s., 0.62 mm; u.c. 1.04)

Filter run	Filtration rate(V_o) m/h	Time hr	Influent turbidity (c_o) NTU	Turbidity at indicated depths (c), NTU					Headloss at indicated depths, cm				
				11 cm	19 cm	29 cm	41 cm	68 cm	11 cm	19 cm	29 cm	41 cm	68 cm
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1a	5.0	0.50	11.50	5.10	2.60	1.90	0.90	0.60	7.7	10.6	13.7	17.9	24.4
		2.00	10.00	3.10	1.40	0.60	0.60	0.40	10.8	14.0	16.2	21.4	27.8
		3.50	9.50	3.80	3.80	0.70	0.60	0.50	13.7	17.0	19.9	23.8	29.5
		6.00	10.00	3.30	2.50	0.65	0.60	0.50	19.5	22.9	26.0	29.6	35.3
		9.00	9.50	6.80	6.80	1.10	0.75	0.45	31.0	34.8	38.2	42.0	47.8
		12.00	10.00	20.00	15.00	1.75	0.65	0.45	46.6	51.2	54.7	58.2	63.8
1b	5.0	0.50	10.50	6.80	3.70	1.40	0.80	0.50	5.2	8.3	11.6	16.0	21.3
		2.00	9.50	2.40	1.70	0.65	0.50	0.35	6.5	9.4	12.2	16.6	21.4
		3.50	9.50	3.20	2.10	0.85	0.80	0.40	10.5	13.9	17.2	21.6	27.6
		6.00	10.00	3.70	3.20	0.85	1.00	0.50	17.2	20.6	23.8	27.7	33.4
		9.00	10.50	5.70	4.80	1.60	0.80	0.55	23.5	27.6	31.0	35.4	40.6
		12.00	10.00	11.00	6.50	1.10	0.90	0.55	42.6	47.6	51.6	55.6	61.8
1c	5.0	0.50	10.00	5.00	1.60	1.00	0.80	0.55	4.9	7.6	10.3	14.0	19.5
		2.00	10.00	3.20	2.10	0.75	0.60	0.40	7.5	10.5	13.5	17.2	23.2
		3.50	9.80	12.00	2.50	0.80	0.70	0.45	10.7	13.9	16.9	21.0	26.4
		6.00	9.00	9.00	3.70	0.85	1.00	0.55	18.5	22.1	25.4	29.2	35.3
		9.00	9.50	4.80	2.80	0.80	0.60	0.40	30.6	35.0	38.1	41.7	47.6
2a	5.0	0.50	25.00	3.40	2.80	1.10	0.75	0.40	5.8	8.3	10.7	13.8	19.1
		2.00	23.50	13.60	8.00	1.20	0.65	0.40	15.1	17.7	19.9	23.1	27.9
		4.00	23.00	14.50	7.60	1.10	0.50	0.40	29.3	42.5	45.4	48.5	54.1
		6.00	24.00	45.00	4.60	3.20	0.80	0.50	76.5	80.0	82.8	86.1	90.8
		8.00	25.00	48.00	20.00	1.70	0.60	0.45	120.8	125.1	128.5	131.5	136.1

Contd...

Table C3 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
		0.50	23.50	9.00	5.50	1.60	1.20	0.60	6.8	9.5	12.1	15.8	21.7
		2.00	22.50	10.00	5.00	0.90	0.60	0.40	15.2	17.9	20.2	23.1	27.7
2b	5.0	4.00	25.50	15.60	6.00	1.90	0.50	0.35	41.4	45.4	48.1	51.3	55.3
		6.00	26.00	30.00	20.00	1.70	0.60	0.35	97.3	104.0	107.7	110.9	115.8
		8.00	25.00	45.00	22.00	4.20	3.30	0.50	165.3	179.8	180.8	183.5	187.5
		0.50	27.00	6.60	2.90	1.10	0.85	0.60	6.6	9.4	12.3	15.8	21.0
		2.00	26.50	13.40	5.80	1.20	0.85	0.50	15.5	19.1	22.1	25.7	30.6
2c	5.0	4.00	25.50	19.50	6.90	1.10	0.55	0.45	34.1	39.0	42.1	45.3	50.0
		6.00	24.50	30.00	10.20	0.85	0.60	0.35	69.7	77.5	81.7	85.1	90.2
		8.00	24.00	40.00	20.00	2.40	0.75	0.40	115.3	127.3	131.9	135.2	139.6
		0.50	10.50	2.20	1.30	1.20	0.90	0.70	6.3	9.8	13.6	18.6	27.3
		1.50	11.00	7.30	2.90	1.40	1.00	0.45	9.2	13.1	17.2	22.5	31.1
3a	7.5	3.00	9.00	7.30	3.80	1.25	0.75	0.50	14.6	19.3	24.0	29.5	38.6
		5.00	9.50	5.80	4.10	1.15	0.75	0.50	24.8	29.2	34.5	40.6	50.2
		7.00	10.00	7.80	8.00	2.30	0.90	0.55	34.0	38.8	44.3	50.0	58.7
		10.00	9.00	8.50	7.40	1.60	0.60	0.50	47.7	56.3	62.4	68.5	77.6
		0.50	11.00	2.30	1.40	0.75	0.60	0.40	6.8	12.2	14.7	19.9	28.8
		1.50	9.50	5.00	4.00	0.90	0.60	0.35	9.2	13.4	17.9	23.6	32.9
3b	7.5	3.00	10.50	4.50	4.00	1.10	0.60	0.40	12.4	16.7	21.1	26.6	35.5
		5.00	10.50	5.30	3.40	1.20	0.65	0.40	20.6	25.6	31.5	37.9	47.6
		7.00	9.50	16.00	4.50	1.00	0.60	0.50	30.1	35.6	40.2	45.6	53.9
		10.00	8.50	30.00	11.50	2.00	0.60	0.50	58.2	64.5	69.6	76.7	82.6
		0.50	11.00	3.30	1.50	1.20	1.00	0.50	8.8	12.0	15.6	20.0	26.0
		1.50	9.50	5.40	3.40	1.00	0.65	0.50	10.9	15.0	19.5	25.2	33.9
3c	7.5	3.00	10.00	5.00	3.00	1.60	0.75	0.45	15.0	19.4	23.9	29.0	36.9
		5.00	11.00	20.00	11.00	3.40	1.20	0.45	31.9	37.3	41.9	47.4	55.3
		7.00	9.50	25.00	9.20	3.40	1.55	0.45	51.6	57.7	64.9	68.1	75.9
		10.00	10.00	17.00	9.20	1.70	0.55	0.45	76.6	104.0	109.4	114.4	131.3

Contd...

Table C3 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
4a	7.5	0.50	25.00	8.20	5.80	1.40	1.00	0.55	9.9	13.8	18.4	24.0	30.2
		1.50	24.50	10.50	7.50	3.40	1.10	0.45	21.1	26.3	30.9	36.6	46.0
		3.00	25.50	17.50	18.00	4.10	1.90	0.60	43.3	50.2	55.6	61.1	69.6
		4.50	26.00	32.00	22.00	3.30	1.10	0.50	77.1	89.0	95.4	100.7	108.8
		6.00	24.00	26.00	24.00	3.10	0.90	0.50	105.6	123.0	129.8	134.8	141.7
4b	7.5	0.50	24.50	14.50	4.10	1.50	0.90	0.60	8.0	12.1	16.2	21.5	30.3
		1.50	25.00	9.00	5.10	1.25	0.75	0.60	14.1	18.8	23.2	28.5	37.0
		3.00	26.50	9.80	6.10	1.40	0.80	0.45	30.7	36.9	42.6	48.4	57.6
		4.50	25.00	40.00	26.00	4.00	1.80	0.65	53.2	58.4	61.4	67.3	80.8
		6.00	24.00	35.00	27.00	4.50	1.10	0.55	76.3	88.4	96.0	102.0	110.4
4c	7.5	0.50	23.00	18.00	7.80	2.60	1.30	0.80	10.0	13.0	16.9	21.6	29.1
		1.50	24.50	7.00	6.80	1.60	0.80	0.55	20.9	27.1	31.1	35.9	43.8
		3.00	24.00	45.00	17.00	5.00	2.40	0.40	48.1	54.1	58.8	64.3	72.7
		4.50	26.00	17.00	20.00	3.80	1.20	0.50	89.3	98.4	103.5	108.2	115.2
		6.00	25.00	55.00	40.00	6.50	1.70	0.50	130.7	145.4	152.0	157.4	165.0
5a	10.0	0.50	10.50	5.00	2.60	1.30	0.90	0.50	11.0	16.2	22.0	29.5	42.3
		1.50	10.00	4.80	3.00	1.50	1.00	0.50	15.5	21.0	26.5	33.6	45.6
		3.00	11.00	3.00	1.50	0.90	0.85	0.70	22.1	28.0	34.2	41.3	52.6
		5.00	8.50	3.80	2.50	0.90	0.80	0.70	58.8	64.5	70.8	77.4	88.1
		7.50	9.50	3.70	2.10	1.00	0.90	0.50	59.5	67.1	74.9	82.6	94.0
5b	10.0	0.50	8.50	4.50	1.80	1.50	0.90	0.45	9.7	14.6	20.6	28.7	43.0
		1.50	9.00	3.80	2.10	0.90	0.80	0.60	14.2	20.0	26.2	34.4	50.0
		3.00	8.50	6.40	5.50	2.00	0.75	0.50	20.5	26.4	33.1	41.8	53.8
		5.00	10.00	16.80	7.80	2.70	1.20	0.55	34.1	42.2	49.1	57.1	68.8
		7.50	10.50	25.00	5.30	1.80	0.70	0.40	61.8	72.0	80.5	88.8	101.1

Contd...

Table C3 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
5c	10.0	0.50	9.00	3.70	2.20	1.15	0.85	0.70	9.9	14.9	20.8	28.7	41.8
		1.50	10.00	4.30	2.40	1.15	0.90	0.60	12.3	17.5	23.6	31.5	43.9
		3.00	10.00	3.30	2.70	1.30	0.90	0.50	17.1	23.3	30.0	38.0	50.7
		5.00	10.50	10.50	12.00	1.90	1.25	0.50	24.5	31.4	38.1	45.8	57.3
		7.50	9.50	11.50	9.80	2.50	1.25	0.45	48.3	57.9	65.5	73.6	85.1
6a	10.0	0.50	24.00	23.00	12.50	2.40	1.50	0.65	8.9	15.4	20.4	26.4	36.0
		1.25	25.50	14.00	10.80	2.60	1.80	0.50	18.8	24.8	30.6	37.2	47.3
		2.00	25.00	22.80	15.00	4.10	1.40	0.50	42.2	57.5	59.1	66.8	78.5
		3.00	23.00	30.00	18.00	4.60	1.30	0.45	66.5	80.5	89.3	97.3	108.4
		4.00	22.50	28.00	29.00	3.80	0.85	0.40	95.2	114.2	123.7	131.0	140.8
6b	10.0	0.50	26.50	29.00	9.00	4.40	2.25	1.25	9.0	13.5	18.7	26.2	37.4
		1.25	25.00	14.30	8.60	1.90	1.30	0.90	12.8	18.4	24.3	31.6	43.2
		2.00	22.50	11.70	8.90	1.60	1.30	0.70	21.9	29.1	36.2	44.1	56.1
		3.00	24.00	37.00	18.00	2.90	0.90	0.60	37.9	46.3	53.6	63.6	73.6
		4.00	23.50	30.00	18.00	4.90	4.00	0.65	59.6	70.8	79.5	88.1	100.5
6c	10.0	0.50	23.50	12.00	6.40	1.90	1.20	0.90	12.1	16.8	21.7	28.3	39.4
		1.25	25.00	26.00	13.00	4.00	1.90	0.45	25.3	31.7	38.1	45.6	58.0
		2.00	24.00	35.00	26.50	6.90	2.70	0.50	41.6	47.9	53.9	60.2	70.5
		3.00	26.00	34.00	19.00	5.20	2.80	0.60	68.1	77.2	84.0	90.3	100.6
		4.00	24.00	50.00	21.00	7.80	4.40	0.50	110.5	126.5	135.0	141.4	152.8

ADDENDUM

The experimental data for the two media were processed using a digital computer incorporating the MARQUARDT program for least square function. The value of the filter coefficient λ_o was expressed by the following equation:

$$\lambda_o = K(\psi d_m)^{-K_1} (v_o)^{-K_2} (c_o)^{K_3}$$

Values of the exponents K_1, K_2, K_3 for the stone-dust and sand obtained by computation are tabulated below.

	Stone-dust		Sand	
	0-11 cm	0-19 cm	0-11 cm	0-19 cm
K_1	0.731	0.745	0.344	0.106
K_2	0.076	0.188	0.233	0.116
K_3	0.226	0.312	0.152	0.161

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